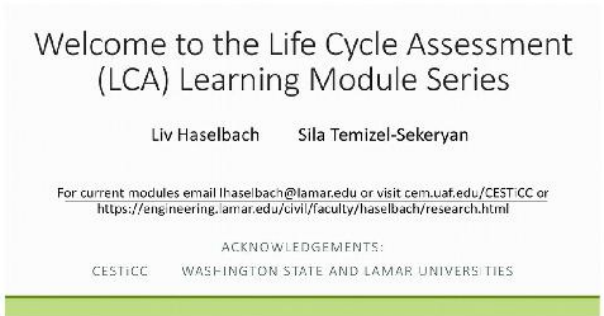
Center for Environmentally Sustainable Transportation in Cold Climates

Transportation Life Cycle Assessment (LCA) Synthesis Phase II



Liv Haselbach and Sila Temizel-Sekeryan
Department of Civil and Environmental Engineering
Lamar University

Date: April 24, 2018

Prepared by: Liv Haselbach and Sila Temizel-Sekeryan

Center for Environmentally Sustainable
Transportation in Cold Climates
Duckering Building Room 245
P.O. Box 755900
Fairbanks, AK 99775

U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

INE/AUTC 2018.07

REPORT DOCUMENTATION PAGE

Form approved OMB No.

Public reporting for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-1833), Washington, DC 20503

1. AGENCY USE ONLY (LEAVE BLANK)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	04/24/2018	Final Report: 06/2017 – 05/2018

4. TITLE AND SUBTITLE Transportation Life Cycle Assessment (LCA) Synthesis Phase II	5. FUNDING NUMBERS 101412
6. AUTHOR(S) Liv Haselbach, Chair and Professor, Lamar University Sila Temizel-Sekeryan, Doctor of Engineering Candidate, Lamar University	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Civil and Environmental Engineering Lamar University P.O. Box 10024 Beaumont, TX 77710	8. PERFORMING ORGANIZATION REPORT NUMBER INE/AUTC 2018.07
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Center for Environmentally Sustainable Transportation in Cold Climates University of Alaska Fairbanks Duckering Building, Room 245 P.O. Box 755900 Fairbanks, AK 99775-5900	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLENMENTARY NOTES	
12a. DISTRIBUTION / AVAILABILITY STATEMENT No restrictions	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) The Transportation Life Cycle Assessment (LCA) Synthesis includes an LCA Learning Module Series, case studies, and analytics on the use of the modules. The module series is a set of narrated slideshows on topics related to environmental LCA. Phase I produced 27 modules, and Phase II added 10 more. The modules are available for download on the Lamar CEE website https://www.lamar.edu/engineering/civil/faculty/haselbach/lca-modules.html and on the CESTiCC website http://cem.uaf.edu/cesticc/publications/lca.aspx. The modules are around 20 minutes long and may be used for various purposes such as for class lectures or part thereof, and for background learning in research or application. The modules are organized into four topical areas, each containing overview and detailed modules. The A and α groups cover the international standards that define environmental LCA. The B and β groups summarize some of the typical environmental impact categories in LCA. The G and γ groups include software tools for LCA. The T and τ groups focus on the growing field of transportation with respect to LCA, a complex area of importance. The analytics section provides data on downloads of the modules from the websites and summary survey results from course implementation.

14- KEYWORDS : Please be sure they are searchable in the Transportation Research Thesaurus http://trt.trb.org/trt.asp? Life cycle assessment, environmental impacts	15. NUMBER OF PAGES 71
	16. PRICE CODE N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	N/A

NSN 7540-01-280-5500

STANDARD FORM 298 (Rev. 2-98)
Prescribed by ANSI Std. 239-18 298-1

DISCLAIMER

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document. The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Opinions and conclusions expressed or implied in the report are those of the author(s). They are not necessarily those of the funding agencies.

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4		mm	mm	millimeters	0.039	inches	in
ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	cm^2	mm^2	millimeters squared	0.0016	square inches	in^2 m^2
ft^2	square feet	0.0929	meters squared	m^2	meters squared		10.764	square feet	ft^2 km^2
yd^2	square yards	0.836	meters squared	m^2	kilometers squared		0.39	square miles	mi^2 ha
mi^2	square miles	2.59	kilometers squared	km^2	hectares (10,000 m^2)		2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb mg
T	Short tons (2000 lb)	0.907	megagrams	mg	megagrams (1000 kg)		1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC	ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

32 98.6 212ºF
-40ºF 0 40 80 120 160 200
-40ºC -20 20 40 60 80
0 37 100ºC

ACKNOWLEDGMENTS

The authors are grateful for support from the Center for Environmentally Sustainable Transportation in Cold Climates, the Washington State Department of Transportation, Washington State University, the Fulbright Program, Lamar University, the National Asphalt Pavement Association, and the Ready Mixed Concrete Research and Education Foundation. We would like to thank the students at the Federal University of Rio Grande do Sul in Porto Alegre, Brazil, at Washington State University, and at Lamar University for being the first to use these modules in classes. Special thanks to Quinn Langfitt for his work on Phase I.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Transportation Life Cycle Assessment (LCA) Synthesis includes an LCA Learning Module Series, case studies, and analytics on the use of the modules. The module series is a set of narrated slideshows on topics related to environmental LCA. Phase I produced 27 modules; Phase II, summarized herein, added 10 more. The modules are available for download on the Lamar University Civil and Environmental Engineering (CEE) Department website https://www.lamar.edu/engineering/civil/faculty/haselbach/lca-modules.html and the Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) website http://cem.uaf.edu/cesticc/publications/lca.aspx. The modules are around 20 minutes long and may be used for various purposes such as for class lectures or part thereof, and for background learning in research or application.

The series is organized into four topical areas, each containing overview and detailed modules. The A and α groups cover the international standards that define environmental LCA. The B and β groups summarize some of the typical environmental impact categories in LCA. The G and γ groups include software tools for LCA. The T and τ groups focus on the growing field of transportation, a complex area of importance in LCA. The educational efficacy section provides analytics on downloads of the modules from the websites and summary survey results from course implementation.

CHAPTER 1.0 INTRODUCTION

Life cycle assessment (LCA) is a tool that is used to evaluate products, processes, or systems in terms of their environmental performance. In Phase I and Phase II, our research effort was on providing learning modules on LCA, with an additional focus on LCA in the transportation sector. Phase I, which was summarized in the report "Transportation Life Cycle Assessment Synthesis: Life Cycle Assessment Learning Module Series (Phase I)" (Haselbach and Langfitt 2015), includes a set of online and pre-recorded learning modules about LCA and an introduction to transportation LCA. The module series is organized into four overall groups. Each group has overview modules (named with capital letters) and detailed modules (named with Greek letters). In the overview modules, broad and basic information and an interactive self-assessment quiz at the end are provided. In the detailed modules, in-depth information on specific topics and a few suggestions for homework problems at the end are presented. The module names are as follows:

- Group A and α: ISO Compliant LCA
- Group B and β: Environmental Impact Categories
- Group G and γ: General LCA Tools
- Group T and τ: Transportation-related LCA

Phase II, reported herein as "Transportation Life Cycle Assessment Synthesis Phase II," mainly focuses on the growing information of transportation LCA. This area of LCA is considered complex because the use phase of an LCA is large in the transportation sector and not well developed. This report summarizes newly added detailed modules, which include information on a case study related to Washington State Ferries, recycling typical roadway materials, recycled materials in roadway construction, deicing chemicals for winter maintenance, and feedstock energy implications for asphalt. The section on a pervious concrete case study includes a literature review of pervious concrete LCAs and a chapter on educational efficacy, in which some analytics collected from websites for accessing the modules are provided. The results of a survey conducted at Lamar University about an LCA course using these modules are interpreted.

Each module is approximately 20 minutes long, which makes the modules useful as lecture material and/or for independent learning purposes. In 2015, these modules were used in teaching a course on LCA at Washington State University (WSU), and as a short course at the Federal University of Rio Grande do Sul, Porto Alegre, Brazil. In 2017, the CEE Department at Lamar University used these modules in an LCA course offered for graduate students. Phase I includes 27 modules. In Phase II, 10 more modules were added. These modules are available for download on the Lamar University CEE Department website https://www.lamar.edu/engineering/civil/faculty/haselbach/lca-modules.html and on the CESTiCC website http://cem.uaf.edu/cesticc/publications/lca.aspx.

The information presented in each module is outlined in the following chapters.

CHAPTER 2.0 GROUPS A AND α: ISO COMPLIANT LCA

In Phase I of this project (Haselbach and Langfitt 2015), two overview modules and six detailed modules were presented for Groups A and α, as summarized in this chapter. The modules focus on the widely accepted international standards for preparing life cycle assessments (LCAs), as found in ISO 14040:2006 and ISO 14044:2006 (ISO 2006 a, b). In Phase II, Module α7 (Feedstock Energy and Carbon Accounting for Asphalt and Other Materials) was added to these groups, as detailed in Section 2.1. All module names may be found in Appendix A.

In Module A1 (Introduction to Life Cycle Assessment and International Standard ISO 14040), an overview of LCA methodology by following the outline of the standard is provided. Definition, general principles, and phases of an LCA are examined, and ISO 14040:2006 is introduced. In Module A2 (LCA Requirements and Guidelines: ISO 14044), the requirements for carrying out an LCA are covered by explaining each component (goal statement and scope elements) in detail. Additionally, life cycle inventory (LCI), life cycle impact assessment (LCIA), mandatory elements (impact category selection, characterization, classification, category indicator selection, and impact methodology) and optional elements (grouping, weighting, normalization, and additional data quality analysis), and interpretation steps are defined. Information on a critical review is included, and ISO 14044:2006 is introduced.

In Module α1 (Goal, Function, and Functional Unit), the mandatory items of goal statement and functional unit in ISO-compliant LCA are covered, illustrated by examples from the literature. In Module α2 (System, System Boundary, and Allocation), process, unit process, system boundary, and cut-off criteria are defined as allocation terminologies. Different examples of system boundaries are illustrated, and various allocation schemes are examined. In Module α3

(Life Cycle Stages), the difference between the phase and the stage of a product life cycle is discussed. Cradle-to-gate (producing the product), cradle-to-site (producing the product and transporting it to the customer), cradle-to-construction (cradle-to-site and constructing the building), and cradle-to-grave (all stages, including disposal or reuse) approaches are characterized with a transportation focus. Life cycle assessment stages are detailed as follows: (1) raw materials and upstream processing; (2) manufacture (including assembly, transportation between facilities, and packaging); (3) use; and (4) disposal/recycling/reuse, with transportation processes in between. In Module α4 (LCIA Optional Elements: Grouping, Weighting, and Normalization), three of the four optional elements—grouping, weighting, and normalization—are discussed by providing figures from the literature. An example from a software tool (BEES) (Lippiatt 2007), which uses weighting in its output, is given. In Module α5 (Data Types and Sources), primary data (directly measured by the researchers), secondary data (obtained from databases, literature, etc.), and estimated data terms are discussed by providing papers that include LCA case studies. Several databases are presented by including information on who produced the data set, how many products/processes are covered and whether they must be paid for or are free, the industry focus of the products/processes (if applicable), and how the data set can be obtained. Lastly, in Module α6 (Environmental Product Declarations), environmental product declarations are defined by mentioning their relationship with LCA and related ISO standards (ISO 14025 Type III Environmental Declarations). The overall objective and required and optional contents of an environmental product declaration (EPD), according to ISO 14025 (ISO 2006c), are presented. Product category rules (PCRs) and a sample listing of program operators (companies and organizations that produce PCRs) are introduced. Additional information may be found in the CESTiCC Phase I report (Haselbach and Langfitt 2015).

2.1 Module α7: Feedstock Energy and Carbon Accounting for Asphalt and Other Materials

Module α7 was added in Phase II. Feedstock energy is first defined using a definition from ISO 14040 (2006a) page 3, which states that feedstock energy is “the heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in the terms of higher heating value or lower heating value,” with a special note that “care is necessary to ensure that the energy content of raw materials is not counted twice.” Feedstock energy or its equivalent tends to be found in a “resource use” section in environmental reporting, not in an impact assessment section. In many documents, the equivalent of feedstock energy is referred to as “Use of non-renewable primary energy used as raw materials” or “Use of renewable primary energy resources used as raw materials,” depending on the source. Table 2.1 gives examples of “Parameters Describing Resource Use” (BS EN 2012); the red rows represent feedstock energy equivalent terminology.

Table 2.1 Parameters describing resource use (BS EN 2012)

Parameter	Unit (expressed per FUn or DUn)
Use of renewable primary energy excluding renewable primary energy resources used as raw materials	MJ, net calorific value
Use of renewable primary energy resources used as raw materials	**MJ, net calorific value**
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value
Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	MJ, net calorific value
Use of non-renewable primary energy resources used as raw materials	**MJ, net calorific value**
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ, net calorific value
Use of non-renewable secondary fuels	MJ, net calorific value
Net use of fresh water	m^3

The FUn in Table refers to functional unit, and the DUn refers to declared unit.

After definitions of feedstock energy and its equivalent nomenclature are provided, an overview of different sources for information gathering (e.g., life cycle assessment, life cycle inventory and other environmental assessments, reports from scientific and industrial organizations, EPDs, PCRs, databases, and tools) is examined for the paving, construction, roofing, wood, flooring, plastics, and agricultural fertilizers industries. Figure 2.1 is a numerical analysis in terms of industry and existence of feedstock energy or equivalent definition. Following this analysis, examples from several resources are presented by grouping similar industries and including their system boundaries.

	EPD	PCR
Pavement - Total	30	14
Other Industries - Total	27	15
Pavement - No data found related to feedstock energy	12	2
Other Industries - No data found related to feedstock energy	2	6

Figure 2.1. Numerical analysis of reviewed EPDs and PCRs (Haselbach 2017)

Two LCA case studies (Butt et al. 2014, Ventura and Santero 2012) are examined to show the interpretation of feedstock energy in very different lights: one positive, the other negative. Butt et al. (2014) page 294, mentioned that feedstock energy in a life cycle study might be considered as “borrowed from the nature,” for generating energy, and as stored within asphalt materials when not consumed. On the other hand, in Ventura and Santero (2012) page 3, feedstock energy is defined as “when organics are used as materials, the energy associated with much of this input remains incorporated in the product.” Thus, these authors consider feedstock energy that is not combusted as “a loss of available resource.”

In terms of carbon accounting, asphalt, concrete, and wood carbon cycles are examined separately and then compared. In the case of asphalt, Peng et al. (2015), who focused on calculating carbon emissions stage by stage for asphalt mixture production and asphalt mixture construction, found that the biggest share comes from heating aggregates with asphalt, followed by the mixing process. However, they found that carbon in the bitumen is not calculated in a carbon cycle, but the energy still contained in the bitumen (feedstock energy) is sometimes added into an energy demand to various life cycle gates, even though not used as energy. In the case of concrete, Mohareb and Kennedy (2012) published an article that indicates the methodology and assessment for gross urban carbon sinks classified as direct and embodied sinks. Lastly, in the case of wood, Walker et al. (2013) mention that forest biomass should be considered in both the short and the long term for its costs and benefit over fossil fuels. To illustrate this, researchers compared conventional technologies (burning fossil fuels) with burning forest biomass to get the same amount of energy. They found that in the long term, the emitted amount of carbon may be re-sequestered by growing forests, so it may be represented as "carbon neutral." Figure 2.2 is a depiction of the compilation of five carbon flux figures. Biomass, harvested wood product, concrete, and landfill carbon fluxes were studied by Mohareb and Kennedy (2012), and a flux for asphalt was added (Haselbach and Temizel-Sekeryan 2018).

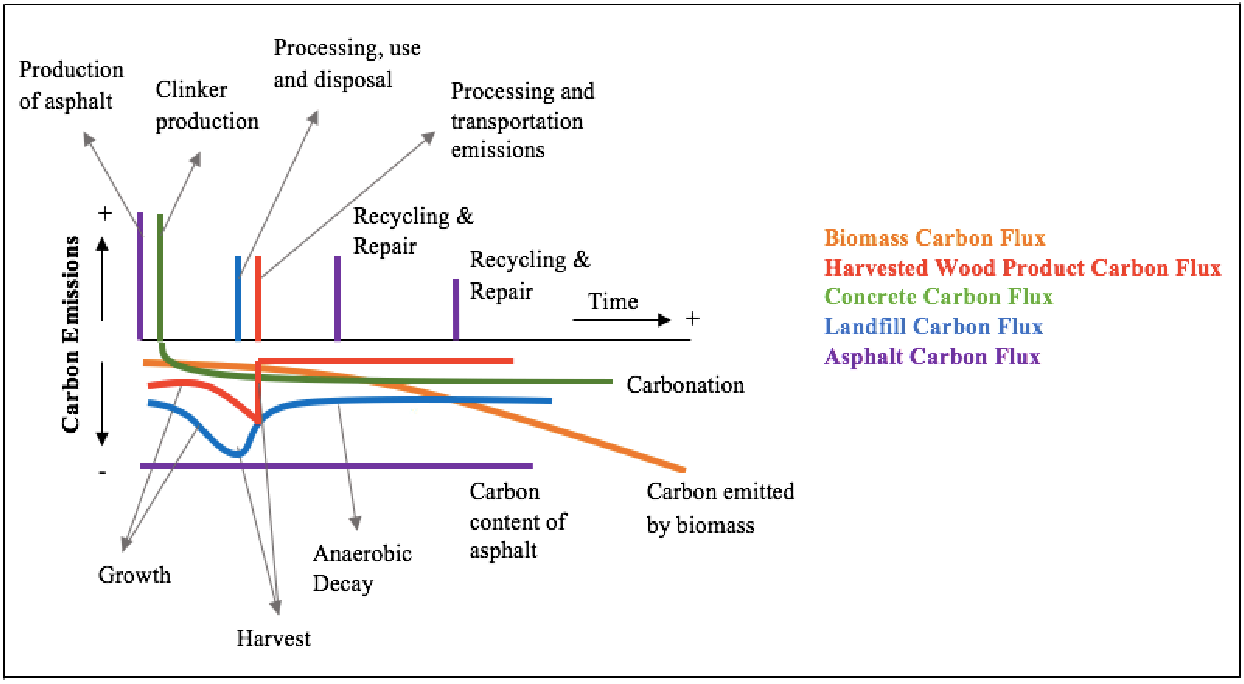


Figure 2.2 Depiction of the compilation of five carbon fluxes (Haselbach and Temizel-Sekeryan 2018)

In conclusion, the importance of carbon and energy accounting while evaluating the environmental performance of a product is mentioned by explaining that information on carbon and energy may be valuable for future decision-making use on energy use or continued sequestration.

CHAPTER 3.0   GROUPS B AND β: ENVIRONMENTAL IMPACT CATEGORIES

In Phase I of this project (Haselbach and Langfitt 2015), three overview modules and eight detailed modules were presented for Groups B and β, as summarized in this chapter. The modules mainly focus on emissions-based impact categories in the life cycle assessment (LCA) literature. All module names are provided in Appendix A.

In Module B1 (Introduction to Impact Categories), a definition of environmental impact category as per ISO is provided (ISO 2006a). Three overall classes of impact categories (human health, ecosystems, and resources) and the most common emissions-based impact categories (acidification, ecotoxicity, eutrophication, global warming, human toxicity cancer, human toxicity non-cancer, human health criteria air, stratospheric ozone depletion, and smog creation potentials) are listed. The relationship between inventory flows and environmental impacts is examined; impact category indicator terminology, including midpoint (direct effects) and endpoint (final effects), is introduced by a reminder that all impacts in LCA are "potential." In Module B2 (Common Air Emissions Impact Categories), four potential environmental impact categories (acidification, global warming, smog creation, and stratospheric ozone depletion) are examined briefly by providing description, the geographic scale of that impact, units commonly used as indicators, major sources (industry/sector), major substances that contribute to the impact category in the United States, and possible endpoints. The concept of Module B3 (Other Common Emissions Impact Categories) is the same as Module B2, in which other impact categories are covered (eutrophication, human toxicity, ecotoxicity, and human health particulates). These potential environmental impact categories are investigated in depth in Group β – detailed modules.

In Module β1 (Global Warming Potential), the definition of global warming potential (GWP), its relationship to climate change, common greenhouse gases, the greenhouse effect term, and major sources and sinks are identified. Global warming potential characterization factors are given for 100-year and 20-year periods, and example calculations are performed. In Module β2 (Acidification Potential), the definition of acidification potential (AP), major substances, scale of impacts, deposition rules, and typical units used to express acidification are covered. The equation for AP is given, and a listing of characterization factors is provided. In Module β3 (Ozone Depletion Potential), the definition of ozone, major contributors, and relationship with additional UV radiation caused by ozone depletion are presented. Additionally, ozone depletion potential chemistry is discussed by providing chemical equilibria. In Module β4 (Smog Creation Potential), the definition of smog, its formation from NOx and VOCs/CO, an equation for calculating the smog creation potential, major sources, possible midpoint/endpoints, and the regional variation of smog are covered. In Module β5 (Eutrophication Potential), the definition of eutrophication potential (EP), its largest forcers (nitrogen and phosphorus), over-nutrification issues, a characterization equation, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) terminology, and possible midpoint and endpoint effects are examined. In Module β6 (Human Toxicity and Ecotoxicity Potentials), human toxicity and ecotoxicity environmental impact potentials are combined because they have similar characteristics. Their definitions, local/regional/global-scale effects, sources, equations for characterization, and a sampling of characterization factors are provided. In Module β7 (Human Health Particulate Matter Potential), the definition of human health particulate matter potential, scale of the impact, characterization and formation of particulate matter, sources, characterization factors, and possible midpoint and endpoints are investigated. In Module β9

(Impact Assessment Methodologies), different impact assessment methodologies used in the life cycle impact assessment (LCIA) phase are summarized by giving information on their creator, date of last update, geographic area of coverage, any optional data (e.g., normalization reference), and a list of impact categories covered. Methodologies described in this module include Eco-indicator 99 (EI-99 2000), Impact 2002+ (EPFL 2003), LUCAS (Toffoletto et al. 2007), LIME 2 (AIST 2012), TRACI (U.S. EPA 2012b), IMPACT World (CIRAIG et al., 2012), and CML-IA (Acero et al. 2015). Detailed information may be found in the CESTiCC Phase I report (Haselbach and Langfitt 2015). In Phase II, Module β8 (Resource-based and Other Impacts) and Module β10 (Particulate Matter and Effects on GWP) are added to **Groups B and β: Environmental Impact Categories,** summarized as follows.

3.1 Module β8: Resource-based and Other Impacts

Module β8 starts with emphasizing the importance between distinguishing two terms: “environmental impacts” and “resource use.” Previously in Module β1 to Module β7, common environmental impacts were covered. In this module, other common LCA categories on resource use are investigated in more detail, including resource depletion, water use, energy use, and land use. Additionally, odor and noise environmental impact categories are mentioned.

Resource depletion is detailed by giving definitions and examples for both abiotic and biotic resource depletion. A screenshot of the introduction slide is given in Figure 3.1. Following the introduction, example characterizations of biotic and abiotic resource depletion are shown by giving formulas for calculation.

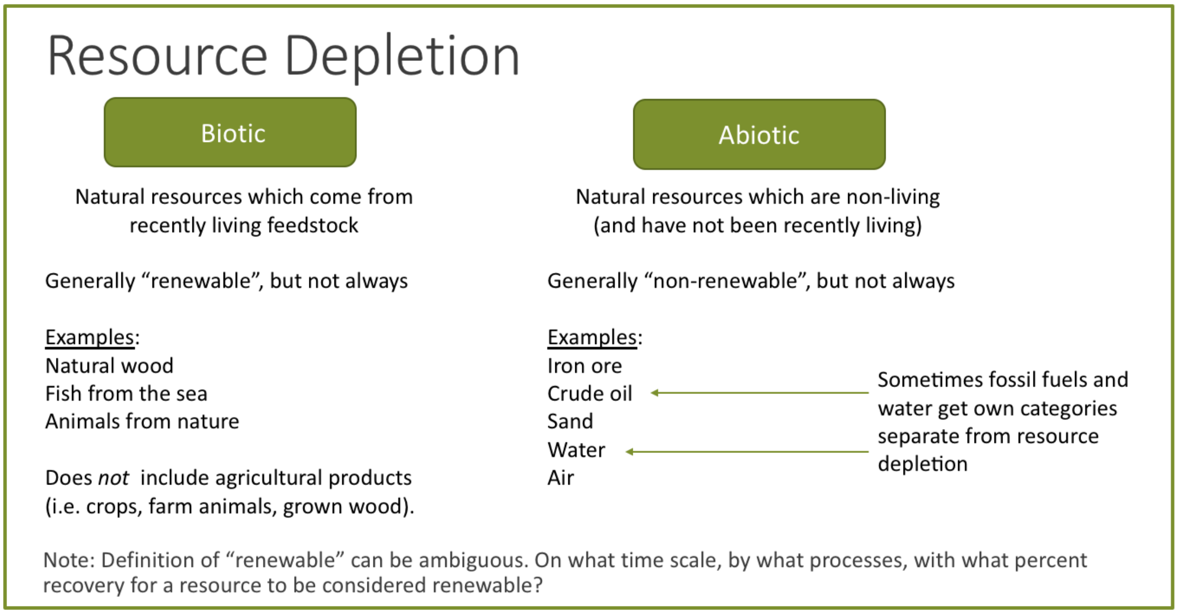


Figure 3.1 Introduction to resource depletion

In terms of water use, consumptive, regenerative, and degradative use concepts are defined with examples. Regenerative water use might not cause resource depletion; cooled cooling water is an example of this type of water use. Consumptive water use likely causes resource depletion, but clarification on whether it has effects on groundwater or surface water is needed. For degradative water use, process water is a good example, since it may contaminate more water than is being "used" or it may be returned not significantly affected. Typical midpoints and endpoints are mentioned, and regional variability (Averyt et al. 2011) is detailed, as shown in Figure 3.2.

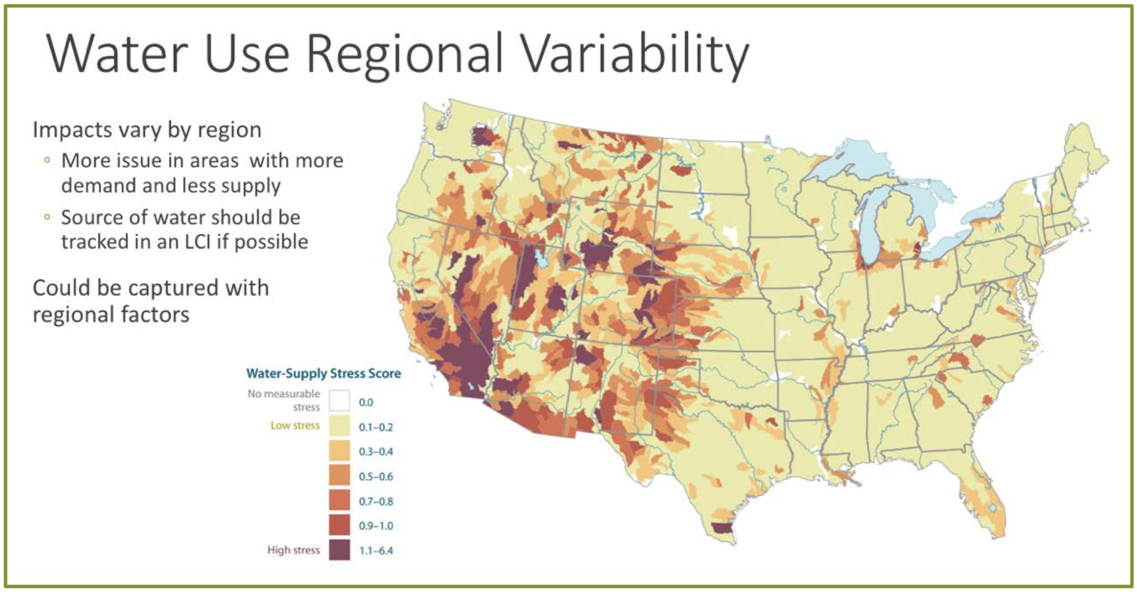


Figure 3.2 Water use regional variability (Averyt et al. 2011)

Energy definitions used in LCA and other standards may differ. Embodied energy, energy demand, and energy content (feedstock energy) terms are defined and schemes are provided. Embodied energy is the energy needed to produce the product. In the Athena Impact Estimator Handbook, it is reported that "embodied primary energy includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources" (Athena Institute 2014 page 47). Sometimes disposal energy is included as well. Energy demand is the energy used over the entire product life cycle, including production, use, and disposal phases. Energy content is the total energy output when the material is combusted. In a handbook published by the European Commission, it is reported that energy content might be given in the lower calorific value measured as MJ, and "the biomass of primary forests, peat and some other biogenic energy resources should be counted as non-renewable" (EC 2010 page 65). Figure 3.3 is an example scheme, drawn to define embodied energy.

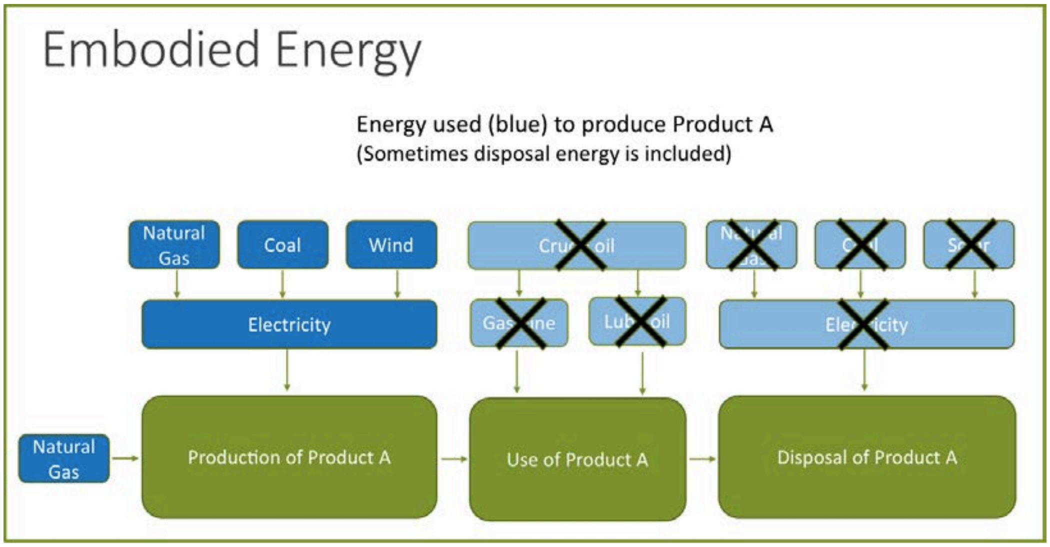


Figure 3.3 Scheme for embodied energy

Energy use terminology, including fossil energy, renewable energy, cumulative energy demand, secondary energy demand, and net energy balance, is defined, and schemes are provided for each term. Some definitions are (1) Fossil energy is "just the energy used that came from fossil fuels, in terms of the energy content of those fuels used"; (2) cumulative energy demand is "total energy used for the product over the life cycle in terms of energy content of sources"; and (3) net energy balance is "cumulative energy demand minus the energy content of the product." Figure 3.4 is an example scheme for net energy balance.

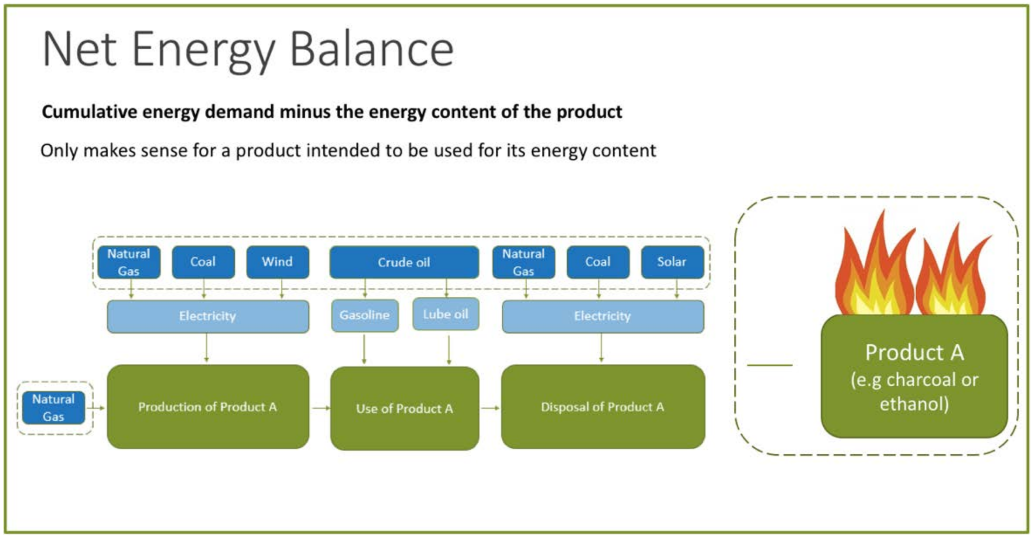


Figure 3.4 Scheme for net energy balance

Another common category in LCA is land use, which is investigated in this module as well. There are two different approaches to land use: (1) competition and (2) transformation. In competition, land can be seen as a limited resource for production. In transformation, loss of biodiversity measured by species density and loss of life support measured by net primary production are considered.

Odor and noise impact categories are briefly addressed. Their characterization units are provided: for odor, "odor threshold values" (OTVs) and for noise, "disturbed human hours." Indoor air and radiation impact categories are also mentioned as developing LCA impact categories.

3.2 Module β10: Particulate Matter and Effects on GWP

Module β10 contains some of the scientific concepts and issues related to particulate matter (PM) and its effects on global warming potential. First, definitions on particulate matter and aerosols are provided, and example pictures are shown (Figure 3.5).

Figure 3.5 Example pictures for aerosols and particulate matter used in the presentation

Absorption versus reflection terminology is illustrated, and the term *black carbon* (BC) is defined as "a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths." Different types of particles may have different effects. Particle transformation in the atmosphere from the point of emission to deposition consists of a variety of physical and chemical processes contributing to changing the light-absorption capacity of a fresh plume. Figure 3.6 from U.S. EPA (2012a) is an illustration of the transformation path of particulate matter.

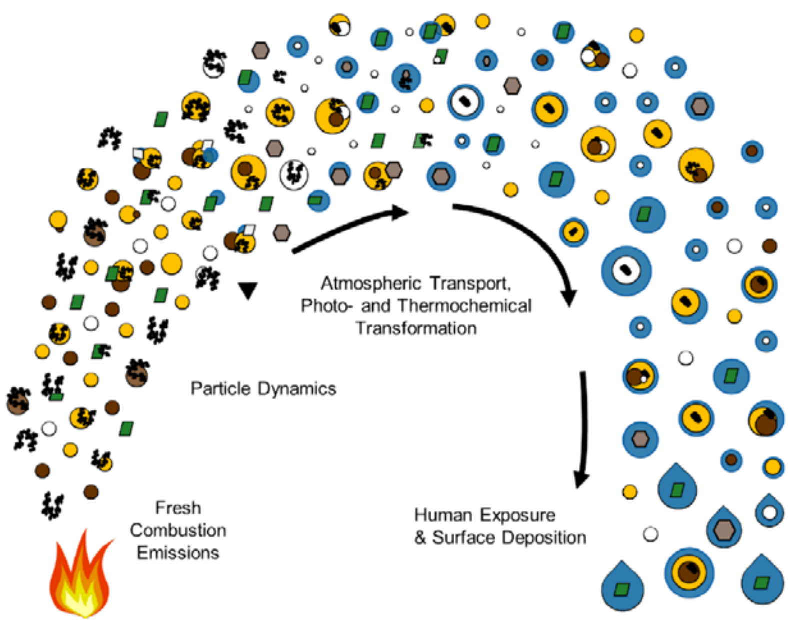


Figure 3.6 Example transformation path of particulate matter (U.S. EPA 2012a)

Interactions of PM and solar radiation are investigated. Their association with the greenhouse gas effect, which might result in warming the Earth's surface and the lower atmosphere, is mentioned. The main sources of PM are then covered, with a comparison of global and U.S. sources. Figure 3.7 is a screenshot showing diagrams on PM sources.

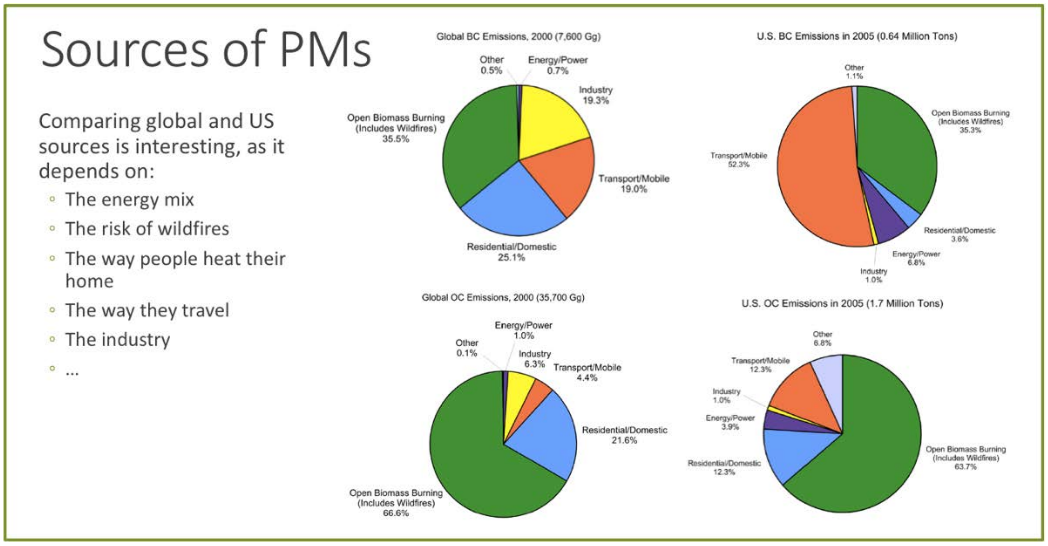


Figure 3.7 Sources of PM

From a LCA perspective, different LCIA methodologies are investigated including CML-IA, TRACI, EDIP2003 (Potting and Hauschild 2004) and ReCiPe (Goedkoop et al. 2009). In these references, we found no factors used to calculate the effects of organic carbon or black carbon on GWP. However, the IPCC (Intergovernmental Panel on Climate Change) gives GWP characterization factors for black carbon and organic carbon from the literature (IPCC 2013). Figure 3.8 is an example that includes both CML and IPCC global warming potential characterization factors.

Global Warming Potential (GWP) characterization of BC and OC

GWP from the literature for BC and OC for time horizons of 20 and 100 years

1 kg of substance	GWP_{20} (kg CO_2-e)	GWP_{100} (kg CO_2-e)
BC total, global[c]	3200 (270 to 6200)	900 (100 to 1700)
BC (four regions)[d]	1200 ± 720	345 ± 207
BC global[a]	1600	460
BC aerosol-radiation interaction + albedo, global[b]	2900 ± 1500	830 ± 440
OC global[a]	-240	-69
OC global[b]	-160 (-60 to -320)	-46 (-18 to -19)
OC (4 regions)[d]	-160 ± 68	-46 ± 20

[a] Fuglestvedt et al. (2010).
[b] Bond et al. (2011). Uncertainties for OC are asymmetric and are presented as ranges.
[c] Bond et al. (2013). Metric values are given for total effect.
[d] Collins et al. (2013). The four regions are East Asia, EU + North Africa, North America and South Asia. Only aerosol-radiation interaction is included.

GWP values from CML 2007 (refer to module β1)

1 kg of substance	GWP_{20} (kg CO_2-e)	GWP_{100} (kg CO_2-e)
Carbon dioxide	1	1
Methane	72	25
HCFC-134a ($C_2H_2F_4$)	3,830	1,430
Nitrous oxide	289	298
Nitrogen trifluoride	12,300	17,200
Sulfur hexafluoride	16,300	22,800
Carbon tetrafluoride	5,210	7,390

Figure 3.8 Global warming potential characterization factors, IPCC and CML

Due to the complexity of the effects of particulate matter, in addition to co-emission of different substances and the evolution of these particles over time, it is difficult to quantify the emissions and their effects accurately.

CHAPTER 4.0 GROUPS G AND γ: GENERAL LCA TOOLS

In Phase I of this project (Haselbach and Langfitt 2015), three overview modules and two detailed modules were presented for Groups G and γ, as summarized in the following paragraphs. The modules mainly focus on different options for life cycle assessment (LCA) software tools at the overview level and a tutorial level. All module names may also be found in Appendix A.

In Module G1 (General Paid LCA Software Tools), LCA-paid software tools are summarized, their similarities and differences are examined, and links are provided. Investigated software tools include GaBi (PE International 2012), SimaPro (PRé 2016), Quantis Suite (Quantis 2013), and Umberto (ifu 2016). In Module G2 (Free LCA Software Tools [Non-Transportation]), free LCA software tools that are not related to transportation are summarized, including Open LCA (GreenDelta n.d.), Building for Environmental and Economic Sustainability (BEES) (Lippiatt 2007), Athena Impact Estimator for Buildings (Athena Institute 2014), and Economic Input-Output Life Cycle Assessment (EIO-LCA) (CMU 2015). In Module G3 (Transportation LCA Software Tools), tools for LCA in the transportation sector are covered, including GREET (Greenhouse Gases, Regulated Emission, and Energy Use in Transportation Model) (Argonne National Laboratory 1993), FEC (Fuel and Emissions Calculator) (Georgia Tech 2016), PaLATE (Pavement Life Cycle Assessment Tool for Environmental and Economic Effects) (RMRC-3G 2003), and Athena Impact Estimator for Highways (Athena Institute 2014). Some of these tools are investigated in depth in Group γ – detailed modules.

In Module γ1 (EIO-LCA Tutorial and Links to GaBi Tutorial), the EIO-LCA tool is examined in detail. Its background and working principles are shown with an example, conducted step-by-step for “asphalt paving materials and block manufacturing.” In Module γ2

(Building LCA Software Tutorial), two building-related LCA software tools—BIRDS and BEES—are detailed. For BIRDS, an example of a new commercial building LCA is conducted step-by-step, and results are discussed. For BEES, an example of an individual building material is conducted step-by-step, and results are interpreted. Detailed information may be found in the CESTiCC Phase I report (Haselbach and Langfitt 2015). No module is added to Groups G and γ in Phase II.

CHAPTER 5.0 GROUPS T AND τ: TRANSPORTATION LCA

In Phase I of this project (Haselbach and Langfitt 2015), one overview module and two detailed modules were presented for Groups T and τ, as summarized in this chapter. The modules mainly focus on applications related to the transportation sector. All module names may be found in Appendix A.

In Module T1 (Introduction to Transportation LCA and Literature Review), a literature review of transportation life cycle assessment (LCA) topics is covered. The LCAs conducted on pavement, vehicles, fuel, and infrastructure systems are investigated in terms of their energy, greenhouse gases, and emissions focus and compatibilities with ISO standards.

In Module τ3 (GREET Tutorial), the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) tool is examined in detail, and a case study on production of compressed natural gas is described. Selection of a functional unit in the GREET tool and interpretation of results are shown. In Module τ4 (Athena Impact Estimator for Highways Tutorial), use of the Athena Impact Estimator for Highways is covered by conducting a case study step-by-step. Afterwards, a results page that may be calculated in tabular or graphical format is presented, and an interpretation method for comparative results is discussed. Detailed information may be found in the CESTiCC Phase I report (Haselbach and Langfitt 2015).

In Phase II, Module τ1 (Functional Units in Transportation), Module τ2 (Agency and Hybrid Normalization), Module τ5 (Case Study – Washington State Ferries Oil Filtration), Module τ6 (Asphalt Recycling), Module τ7 (Concrete Recycling), Module τ8 (Stabilization of Dredged Material for Beneficial Uses: A Transportation Challenge), and Module τ9 (Impact of

Deicers on Transportation Systems) are added to Groups T and τ: Transportation LCA. These modules are summarized in the following sections.

5.1 Module τ1: Functional Units in Transportation

Module τ1 starts with a reminder of the definitions of the terms *function* and *functional unit*, and continues with a discussion of the importance of deciding a functional unit by its unit instead of its value. Ideally, the functional unit should include information on the quantity, quality, and duration of producing the function. In this module, some functional units used in the transportation sector are discussed.

First, functional units for vehicle-related (land, water, or air) studies are presented. Examples are as follows: (1) distance driven per vehicle as a quantity indicator, (2) being an express or local line as a quality indicator, and (3) operating hours as a duration indicator. More examples from the literature and a frequency analysis of functional units for vehicle-related studies are provided. As a case study, the ferry system Washington State Ferries is discussed. If just the function of a vessel to move things is considered, possible units may be passenger, vehicle, miles, trips, etc. Other units may be per kWh engine output and 1-year "typical operation." Figure 5.1 is an example screenshot from the Washington State Ferries case study.

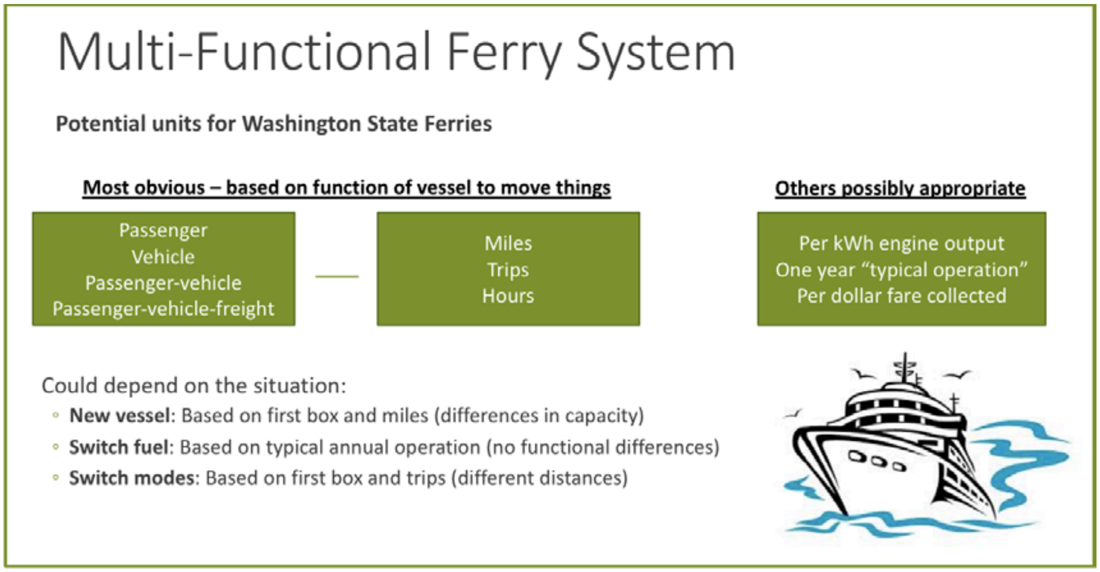


Figure 5.1 Potential functional units for Washington State Ferries

Next, functional units for paving-related studies are presented. Examples are as follows: (1) road length as a quantity indicator, (2) durability as a quality indicator, and (3) service length as a duration indicator. More examples from the literature are provided. Functional units for fuel-related studies are also discussed. Examples include (1) distance as a quantity indicator, (2) renewability as a quality indicator, and (3) storage life as a duration indicator. Here a note is given which indicates that quantity and duration may be linked in some cases for fuels. More examples from the literature are provided.

A case study by Choudhary et al. (2014) is examined to express the importance of functional unit selection. The aim of Choudhary et al., illustrated in Figure 5.2, was to compare the life cycle emissions of bioethanol and bioelectricity using different functional units. The researchers found that the bioethanol pathway produces a larger environmental footprint in terms of global warming potential than the bioelectricity pathway on a per-unit-energy-content basis or a per-unit-area-of-cropland basis. However, the bioethanol pathway can offer more offsets than the bioelectricity pathway on a per-vehicle-kilometer-traveled basis when using bioethanol and bioelectricity for vehicle operation.

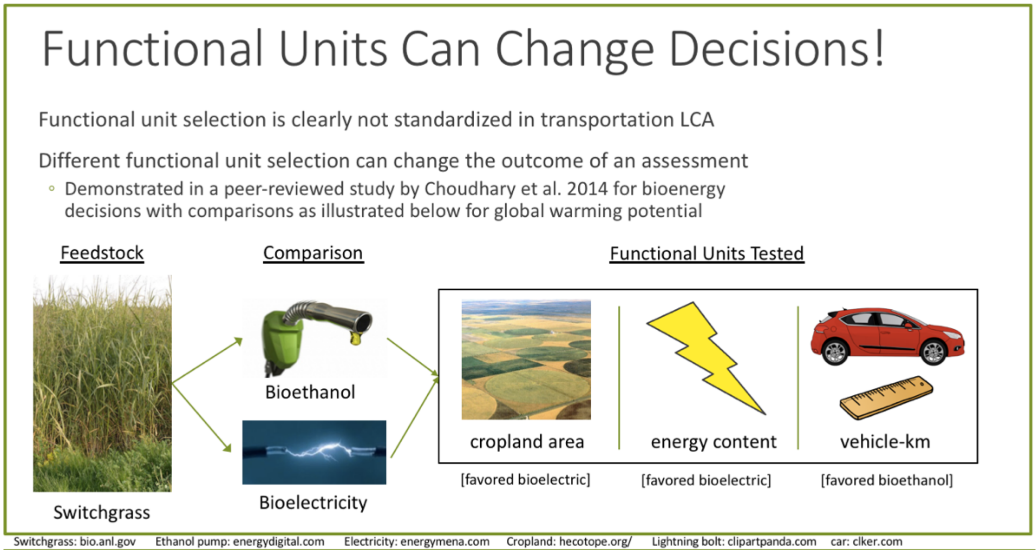


Figure 5.2 Case study on functional unit selection (Choudhary et al. 2014)

There are many options for functional units in each case, which allows high variability in units used in life cycle assessments. Using a declared unit may be an alternative option instead of using a functional unit. Functional units are generally used for decision-making purposes; however, declared units may be useful in the research literature, and the reporting data might be more readily transferable to other research efforts.

5.2 Module τ2: Agency and Hybrid Normalization

Module τ2 starts with definitions and equations of normalization, and then continues with an examination of the potential advantages and disadvantages of transportation agency normalization. Agency normalization has a number of potential benefits over the more common approach of normalization to a geographic reference area. Agency normalization might show the agency what types of changes could improve its overall environmental profile, by comparing impacts of a decision with total agency impacts. However, making improvements to an impact category may make future improvements to that category seem more important (and vice versa). In this module, both U.S. and hybrid normalization are examined.

Before developing hybrid normalization, we provide some terminology to help users understand the new normalization approach. The terminology includes (1) *performance*, which means the environmental LCA impacts of a product or process under study, (2) *entity*, which means the total impacts of a corporation or agency, and (3) *spatial*, which means the total impacts forced in an area of geographic coverage. Following these explanations, normalization types are provided, as given in Figure 5.3 (Langfitt and Haselbach 2017).

Normalization Types based on Naming Scheme

Traditional Name	Factor Name	Description	Example
Internal	Performance/ performance	Impacts of each product normalized by the impacts of another within the study	$\frac{Product\ A}{Product\ B}$
External	Performance/ spatial	Impacts of each product normalized by the impacts in a geographic reference area	$\frac{Product}{US}$
External	Performance/ entity	Impacts of each product normalized by the impacts of a corporation or agency	$\frac{Product}{Agency}$
Not named	Entity/spatial	Impact ratio of a corporation or agency to the impacts in a geographic reference area	$\frac{Agency}{US}$

Note: "product" could also be a process, built element, system, etc.

Figure 5.3 Normalization types based on naming scheme (Langfitt and Haselbach 2017)

Some comparisons of example sets of data are conducted with normalization techniques (Langfitt and Haselbach 2017). Figure 5.4 shows one hybrid normalization style, displaying agency normalization so that decision makers can determine the impact categories to which an agency is contributing significantly. With this combined presentation style, decision makers can get information about a product's contribution to their own agency's decisions, and information about how much emphasis might be given to each impact category. For instance, from Figure

5.4, we can comment that human health cancer and non-cancer seem to be the most important potential environmental impact categories, as the bars are high, but actually, the agency does not contribute to these categories very much as compared with other categories relative to U.S. contributions. This normalization technique may lead to an inverse proportion within the performance/entity results, and decision makers may not conclude that smog creation and acidification potential are hotspots, as may be portrayed in the entity overlaid normalization. After these detailed explanations, the "entity accentuated normalization" technique is briefly covered.

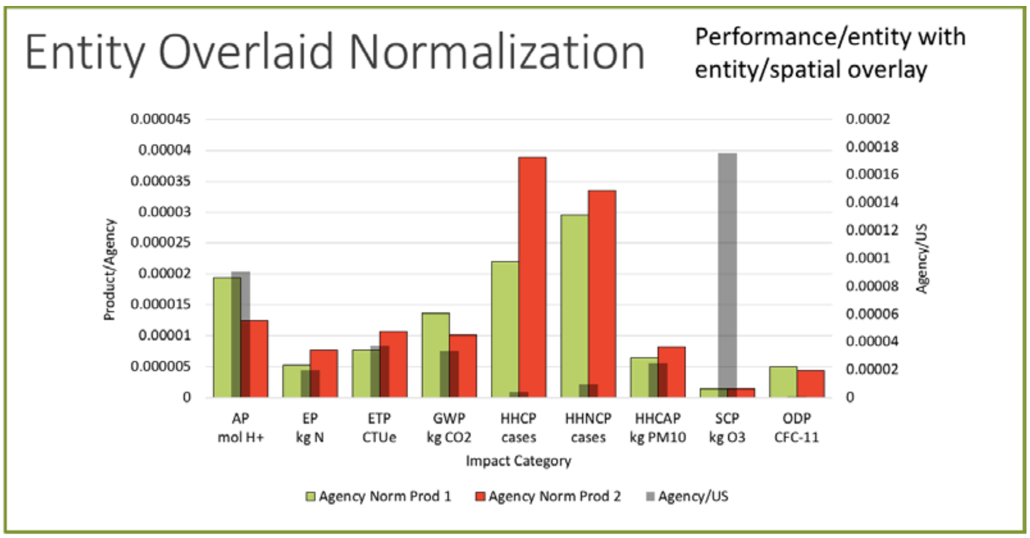


Figure 5.4 Combined presentation style (Langfitt and Haselbach 2017)

Hybrid normalization is presented as a way to bridge entity and regional normalization references; it can also be more widely applied with any external normalization references, taking the place of the entity and regional references.

<u>5.3 Module τ5: Case Study – Washington State Ferries Oil Filtration</u>

In Module τ5, Washington State Ferries (WSF – a division of Washington State Department of Transportation), a ferry operator in the Seattle-Tacoma area, is introduced. A case study for WSF is conducted on an alternative oil filtration technology, a self-cleaning filtration system, for the ferry system's vessels, in terms of evaluating environmental footprints. Figure 5.5 shows a comparison of standard and self-cleaning filtration systems. Also, the system boundary for the standard system is illustrated and detailed.

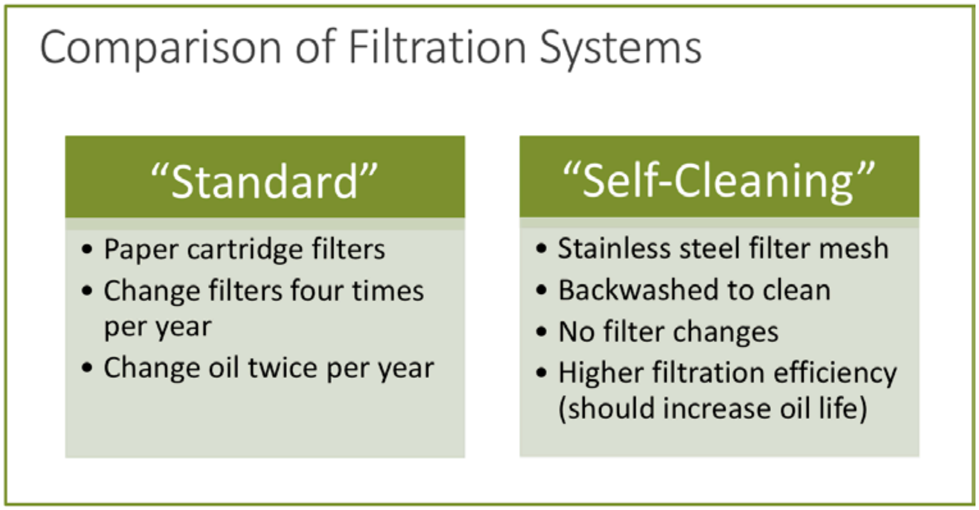


Figure 5.5 Comparison of filtration systems conducted in the case study

Originally in this case study, oil, filter cartridge, and filter housing system had been included (Langfitt and Haselbach 2015). However, this module only covers the oil portion of the case study. Because of the availability and accessibility of oil data, an LCA style data synthesis was used to develop the environmental results. Goal and scope definition, functional unit, and impact category selection are detailed, and environmental data collection is conducted, as shown in Figure 5.6.

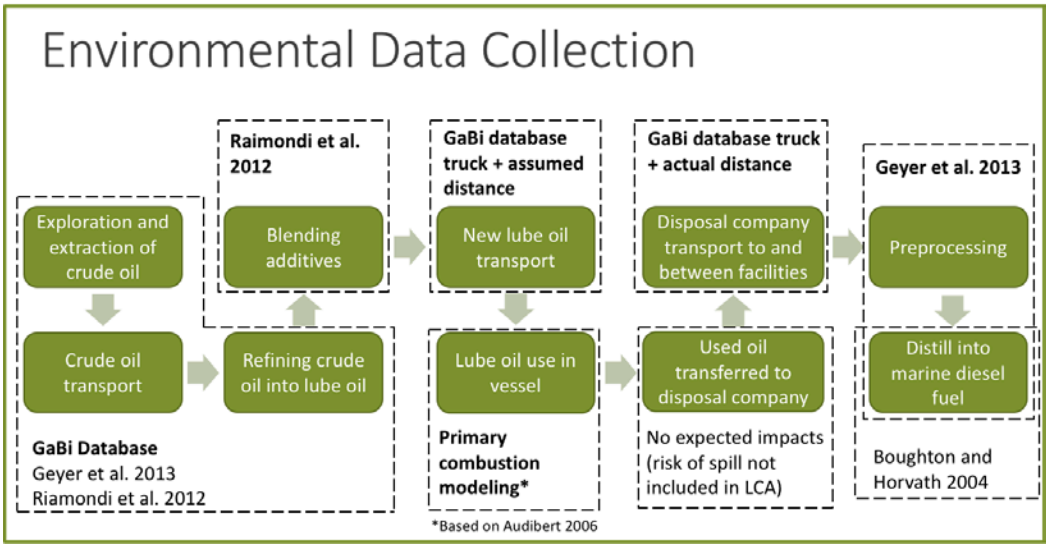


Figure 5.6 Environmental data collection system

General LCA results for base oil production, blending of oil, acquisition transport processes, distillation to marine diesel oil, disposal transport, and displaced primary product are as given in Figure 5.7. To put these results in context, the number of person-day equivalents of impacts is calculated for both acquiring and disposing of 1200 gallons of lubricating oil (assuming that none is combusted in the engine).

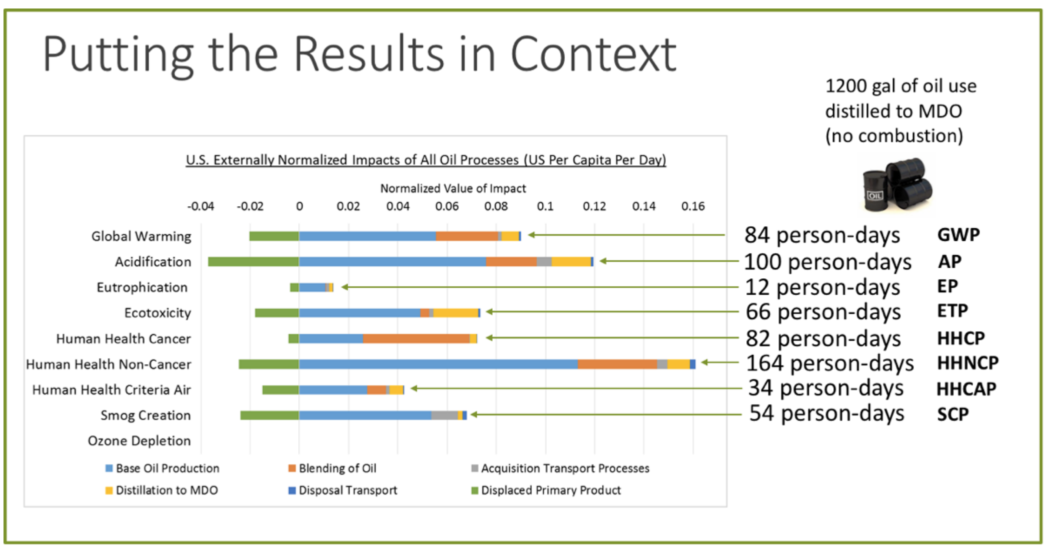


Figure 5.7 Results of the case study (Langfitt and Haselbach 2015)

5.4 Module τ6: Asphalt Recycling

Module τ6 covers the characteristics of asphalt, the industry, and various asphalt recycling options. Environmental product declarations (EPDs) and LCAs from the literature are examined to learn how these characteristics are used in environmental reporting. Statistics are given to understand the scale of the industry (NAPA 2014). Figure 5.8 is a screenshot from this module.

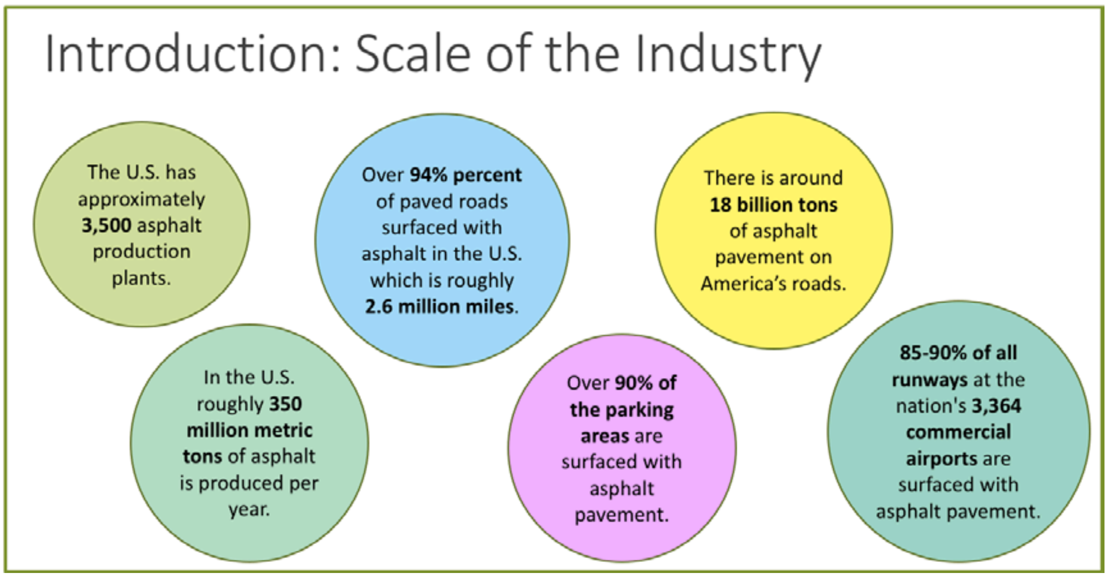


Figure 5.8 Some statistics for the asphalt industry (NAPA 2014)

In terms of the environment, asphalt has three characteristics that might not be captured easily in an EPD: (1) it may have a high recycled content, (2) it is highly recyclable, and (3) it has stored carbon content. Manufacturing with nearly 100% recycled inputs results in an approximately 50% decrease in CO_2 equivalent emissions coming from process energy and transportation energy (U.S. EPA 2015). In addition to the environmental benefits, using recycled asphalt has economic benefits.

There are three different recycling methods for asphalt: in-place recycling, in-plant recycling, and cold planing. In-place recycling has three types of application: full-depth reclamation, hot in-place recycling, and cold recycling. In this module, each method is described, as illustrated in Figure 5.9.

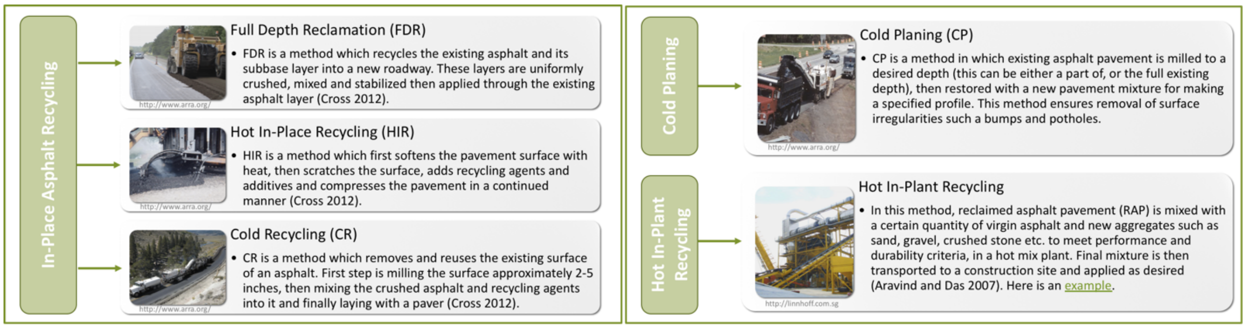


Figure 5.9 Different methods for asphalt recycling covered in module

From EN 15804 (BS EN 2012), which provides reporting of environmental information, "recyclability" is covered in Module D (Benefits and loads beyond the system boundary, information module). In terms of asphalt production, recycled content itself might be handled in fewer potential environmental impacts to the gate in an EPD (Haselbach 2017). Overall, A1 (raw material supply), A2 (transport), and A3 (manufacturing) are required modules in an EPD; others are optional. Therefore, asphalt may be handled in modules A1, A2, A3, and D (Haselbach 2017).

Asphalt schemes in some LCA tools are covered by examining the Athena Pavement LCA (for Canadian and U.S. roadway designs) tool, the BEES 4.0 (Building for Environmental and Economic Sustainability) tool, and the Economic Input-Output Life Cycle Assessment (EIO-LCA) tool.

5.5 Module τ7: Concrete Recycling

Module τ7 provides information from a literature review of concrete recycling and its life cycle assessment. As an introduction, information on concrete production and its effects is provided. Also recycling and the recyclability of concrete and the advantages of using recycled concrete aggregate (RCA) are examined. Environmental advantages, such as resource conservation, reduced land disposal and dumping, conservation of virgin aggregate, reduced impacts to the landscape, and metal recovery are given as examples. Economic advantages may include limited haul distances, reduced disposal costs, overall project savings, and minimized impacts to existing roads with reduced hauling (U.S. FHWA 2004).

In a study conducted by the U.S. Department of Transportation (U.S. FHWA 2004), state transportation agencies were surveyed to determine the current uses of recycled concrete aggregate. Figure 5.10 shows the answers given by each state. From the results of this survey, five states were identified as being among the highest consumers as well as large suppliers of recycled concrete aggregate in the United States. The states are Texas, Virginia, Michigan, Minnesota, and Utah.

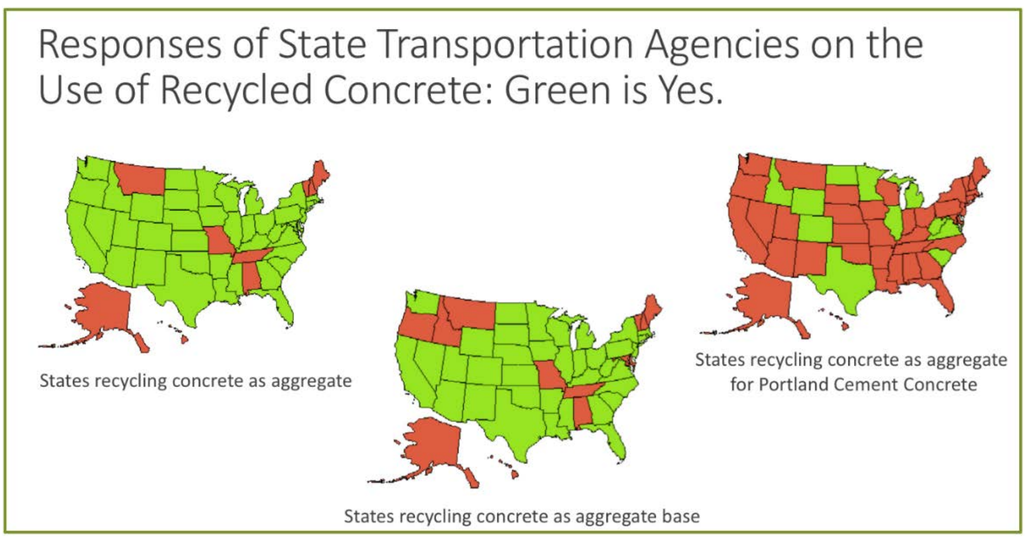


Figure 5.10 Results of U.S. FHWA survey (U.S. FHWA 2004)

For an LCA case study on recycled concrete, Schepper et al. (2014) is examined. In this study, traditional recycling and “completely recyclable concrete” scenarios were investigated. Typically, concrete is recycled as a raw material for aggregate production, whereas “completely recyclable concrete” is used as a raw material for cement production. This study found that global warming potential is reduced approximately 70% by taking the “completely recyclable concrete” path, since raw materials used for cement production are decreased.

Another case study, this one on using recycled concrete in transportation, is examined. In Surya et al. (2013), five concrete mixes, including 50%, 75%, and 100% recycled aggregate concrete with fly ash, and natural aggregate concrete mix with and without fly ash, were studied in terms of their compressive strength, split tensile strength, flexural strength, modulus of elasticity, water absorption, and resistivity. Figure 5.11 is from Module τ7.

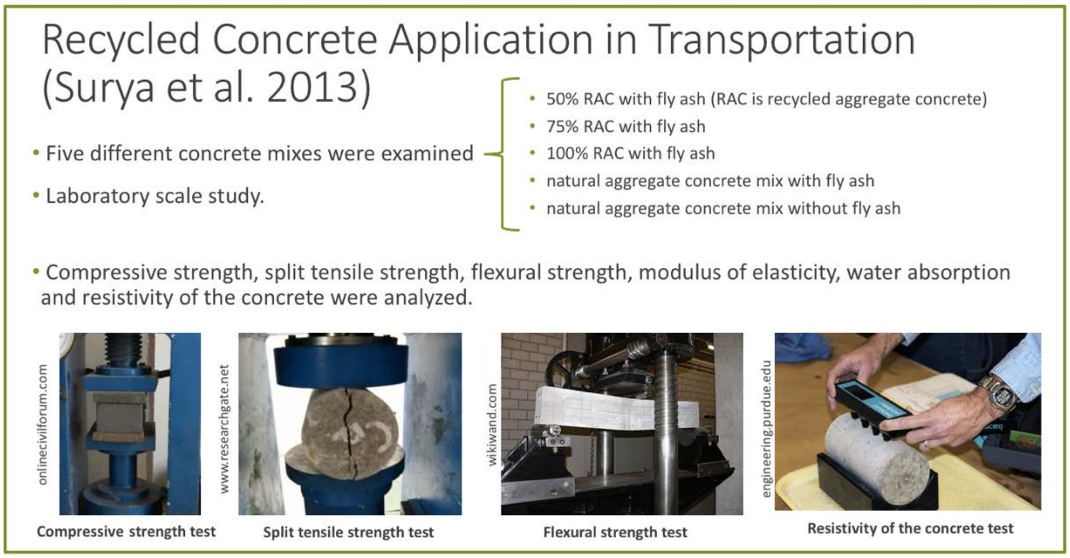


Figure 5.11 Summary of a case study (Surya et al. 2013)

This laboratory-scale study found that the compressive strength, split tensile strength, and flexural strength of concrete is approximately the same among the three different recycled aggregate concrete scenarios. However, further research is needed to determine whether these structures are useful for the construction of transportation infrastructure.

5.6 Module τ8: Stabilization of Dredged Material for Beneficial Uses: A Transportation Challenge

In Module τ8, beneficial uses of dredged material are covered by defining dredged material itself, dredging methods, and dredged material management alternatives. The public thinks that dredged material is commonly contaminated, when in fact a significant portion of material dredged from U.S. waters is not contaminated and is potentially reusable (U.S. EPA 2007). Figure 5.12 shows examples of dredging spots in the U.S.

Figure 5.12 Examples of dredging spot locations in the U.S.

Some examples of beneficial uses are as follows: habitat restoration and development, beach nourishment, artificial islands, parks and recreation, agriculture forestry, horticulture, aquaculture, construction, and industrial development. Material type may be a key for decision making on beneficial use type. For instance, if the material type is rock, habitat restoration and development and beach nourishment may be possible beneficial uses (U.S. EPA 2007).

Additionally, a brief literature survey is covered on the beneficial use of these materials. Grubb et al. (2010) evaluated the possibility of using dredged material as fill for the Virginia Port Authority's Craney Island. The compressive strength properties of stabilized dredged materials were compared, and results showed that dredged material is a good choice for this construction use. Examples also include research from Lamar University, where the feasibility of using dredged material to manufacture sustainable alternatives to armor stone (rip-rap) or blocks or erosion control on berms or levees is being studied.

Only a few studies are using LCA techniques for evaluating dredged material replacement strategies. These studies show that end-of-life scenarios are currently considered in economic and environmental evaluations of dredging options. Bates et al. (2015), who conducted an LCA on dredged material replacement strategies, found that upland placement has significant environmental impacts due largely to fuel use. Figure 5.12 shows the system boundary of this study.

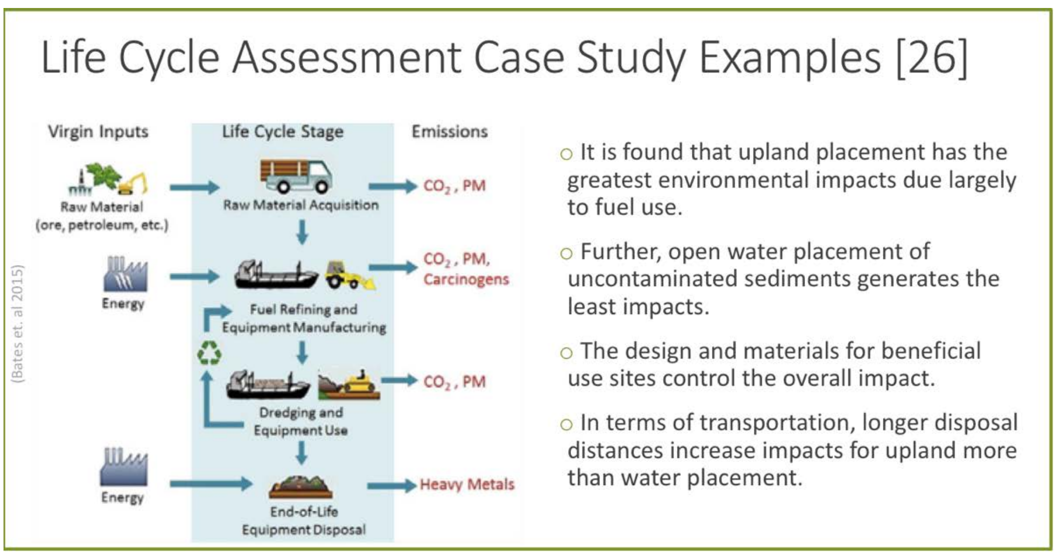


Figure 5.13 System boundaries of Bates et al. (2015)

<u>5.7 Module τ9: Impact of Deicers on Transportation Systems</u>

Module τ9 provides information from a literature review of impacts of deicers on transportation systems and their life cycle assessment. As an introduction, definitions and types of deicers and anti-icers are given, and differences between anti-icers and deicers are discussed. Figure 5.14 is a screenshot from Module τ9.

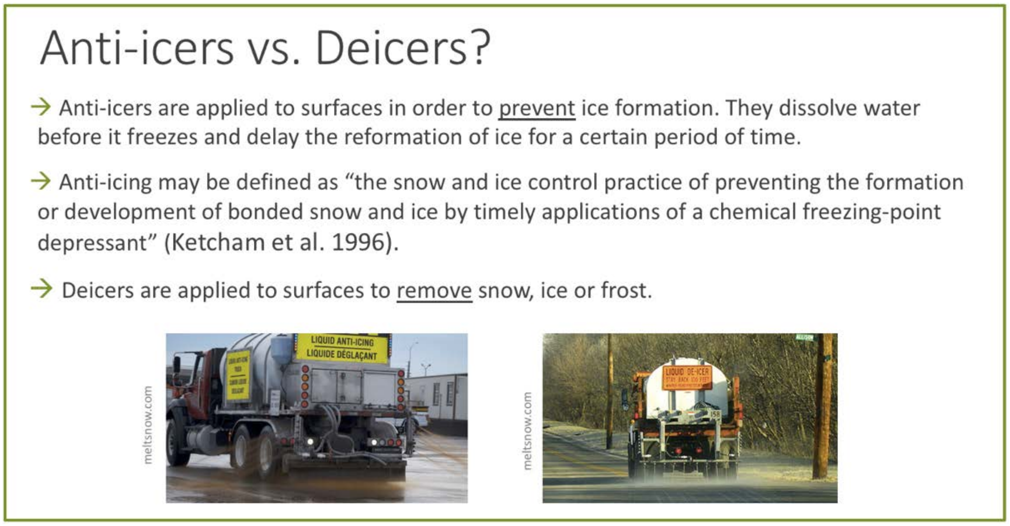


Figure 5.14 Differences between anti-icers and deicers

Note that deicers, used for winter road maintenance, may affect the environment adversely while providing safer roads. Ye et al. (2014) is examined to learn the effects of winter maintenance chemicals on road safety. Statistical results show that the use of winter chemicals can reduce the number of winter crashes and improve road safety. According to Ye et al. (2014), the use of winter chemicals produced more benefits than associated costs. Four studies on modeling road conditions for winter road maintenance operations are suggested.

In addition to road safety, the environmental impacts of deicers are examined in Module τ9. In Fay and Shi (2012), the environmental impacts on soil, flora, fauna, surface and ground waters, and humans are detailed. Figure 5.15 from Module τ9 shows a summary of this paper.

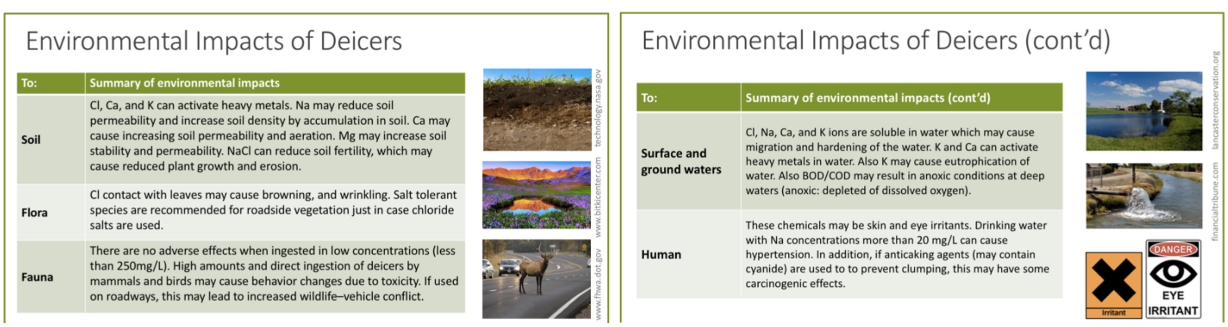


Figure 5.15 Summary of environmental impacts of deicers (Fay and Shi 2012)

An LCA case study on deicer treatment scenarios is analyzed. Environmental life cycle performances of (a) conventional rock salt, (b) sodium chloride brine, and (c) calcium magnesium acetate (CMA) are evaluated by Fitch et al. (2013). System boundaries are selected from raw material acquisition to installation (Modules A1, A2, A3, A4, A5). Sodium chloride brine option is found to be the best among the other scenarios in terms of energy use (MJ), greenhouse gas emissions (kg), water use (m^3), and BOD (kg). Stormwater runoff and storage (Module D) are also considered in sensitivity analysis. Inclusion of further details and impacts of deicers in Module D (Benefits and loads beyond the system boundary, Information Module) may result in different outcomes.

CHAPTER 6.0 PERVIOUS CONCRETE CASE STUDY

Permeable pavements are systems with voids in the pavement layer that enable stormwater to pass directly to an underground storage bed. This underground bed serves as water management, detaining or retaining the stormwater, or a combination thereof. Porous asphalt, permeable pavers, and pervious concrete are examples of permeable pavements. The various types may consist of different layers and features, i.e., surface course, choker course (optional for some), reservoir course, underdrain (as required), filter fabric, and subgrade soil (U.S. EPA n.d.).

Pervious concrete pavements have both advantages and disadvantages over conventional pavements (ACI 2010). Advantages include controlling stormwater runoff and its pollution at the source, reducing noise pollution, allowing air and water to reach tree roots, and supporting natural landscaping applications. Disadvantages include lack of system standardization, limited use in heavy traffic loads, and special construction and curing needs (ACI 2010).

As mentioned before, pervious concrete systems have many beneficial uses, but these are not currently well documented or known from a life cycle perspective. There is a standardized environmental reporting system called Environmental Product Declaration (EPD), which is a "Standardized (ISO) comparable report of the environmental impacts of products from cradle to gate (or grave)" (Simonen and Haselbach 2012 Slide 8). Environmental product declarations are developed by using life cycle assessment (LCA) methodologies. The common methodology for infrastructure is BS EN 15804 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products (BS EN 2012). This standard provides a modular scheme for defining EPD system boundaries, meaning the processes that are covered in determining the environmental impacts and resource use related to the EPD. In Section 5.2 of BS EN 15804, potential modules in a product's life are given as follows:

- Product Stage (Modules A1–A3): Raw material supply (A1), Transport (A2), Manufacturing (A3);
- Construction Process Stage (Modules A4–A5): Transport (A4), Construction/installation process (A5);
- Use Stage (Modules B1–B7): Use (B1), Maintenance (B2), Repair (B3), Replacement (B4), Refurbishment (B5), Operational energy use (B6), Operational water use (B7);
- End-of-life Stage (Modules C1–C4): Deconstruction/demolition (C1), Transport (C2), Waste processing (C3), and Disposal (C4);
- Benefits and Loads beyond the System Boundary (Module D): Reuse/recovery/recycling potential (supplementary information beyond the product life cycle).

Product stage modules (A1, A2, and A3) are required in an EPD according to BS EN 15804; the rest of the product stage modules are optional. Thus, EPDs might not capture the benefits of the use phase. Some benefits of the use phase and a literature review of the limited LCA research on these systems follow.

Wang et al. (2013) evaluated green and gray systems of stormwater infrastructure in terms of their effect on climate, resource use, and economic costs using LCA methodologies for three conditions in the northeast United States (typical, dry, and wet). Gray (conventional) infrastructure collects stormwater runoff and sends it to treatment facilities or discharges it directly to receiving bodies with or without treatment. Inversely, green infrastructure is designed to minimize runoff quantity and provide additional advantages such as habitat improvement and prevention of heat island effects. In the Wang et al. (2013) study, three different “green” systems were investigated: (1) bioretention basins, (2) green roofs, and (3) permeable pavements, all of which are able to filter runoff and remove nonpoint-source pollutants. The researchers found that permeable pavements have large environmental footprints in terms of selected environmental impact categories caused by raw materials acquisition and intensive installation and maintenance processes. Vares and Pulakka (2015) compared conventional pavements and permeable pavements, used in small traffic load areas such as walkways and bicycle lanes, in terms of their environmental and economic performance. Three scenarios may be developed to achieve the same drainage capacity: (1) impermeable pavement with a drainage system, (2) fully permeable pavement without a drainage system, and (3) partly permeable pavement constructed with a small drainage system. Vares and Pulakka (2015) compared conventional asphalt pavement, conventional concrete pavement, concrete paving blocks, permeable concrete pavement, and porous asphalt pavement structures. In calculating the carbon footprint (kg CO_2-eq/30 year) for all compared products for each life cycle stage, the researchers found that the construction stage contribution to overall life cycle is essentially the same for all products. However, the biggest share of production, maintenance, and repair life cycle phases belongs to both conventional and porous asphalt structures. Permeable concrete's share is significant for the maintenance phase, and the conventional concrete share is high in the production stage.

Similarly, the objective of Spatari et al. (2011) was to compare the strategy of containing permeable pavement and street trees with conventional street structure in terms of energy usage and greenhouse gas emissions (CO_2-eq.). The researchers found that annual savings were 1.1% in energy and 0.8% in global warming potential (GWP) compared with the conventional system. These amounts may be considered low, but the researchers emphasized that the results were for 1 year (slow environmental payback period).

Additional literature review on stormwater management LCA was conducted. Sharma et al. (2009) evaluated alternative water servicing scenarios that are used to reduce the amount of stormwater runoff and discharged wastewater. Environmental performance, eutrophication, and greenhouse gas emissions were evaluated for three flows: (1) water, (2) wastewater, and (3) stormwater. The researchers found that wastewater reuse is preferred to stormwater reuse in terms of eutrophication impact. The most environmentally friendly scenarios reported were on-site graywater reuse, rainwater tanks, and on-site wastewater treatment systems.

The objective of De Sousa et al. (2012) was to compare green infrastructures and conventional systems. They examined three different scenarios: (1) a combination of green infrastructure (porous pavements, street-end bioretention bump-out facilities, curbside infiltration planters, backyard rain gardens, and subgrade cisterns); (2) an end-of-pipe detention facility (by construction of a reinforced concrete detention tank); and (3) an addition to an end-of-pipe detention tank, in which detained flow was assumed to be treated (physically and chemically) and discharged directly to the receiving body (in this study, the Bronx River). The GWP was calculated, and Scenario 1 (a combination of green infrastructure) was rated the best.

Using LCA methodologies, Flynn and Traver (2013) evaluated bio-infiltration rain garden (green infrastructure) stormwater control measures. The results of their study showed that operation and decommissioning components greatly impact environmental performance, both positive and negative. In the operation phase, maintenance impacts, urban forest benefits, stormwater management benefits, and combined sewer system benefits were included and detailed. In the decommissioning phase, rain garden media reuse and disposal scenarios were covered.

Green roofs may also be considered as alternatives for stormwater management. Kosareo and Ries (2007) conducted a study to compare green roofs and conventional roofs in terms of their environmental and economic performance. Green roofs may be used to reduce stormwater runoff, may be a solution for the urban heat island effect, and may improve air and water quality. One scenario was related to stormwater runoff, in which researchers proposed to change the quality and quantity of stormwater runoff by applying runoff factors to pollutants. In this study, an intensive green roof (150–1200 mm growing medium) performed the best environmentally by reducing the conventional roof's footprint by 50% in terms of ozone layer depletion, aquatic acidification and eutrophication, and GWP impact. Runoff reduction was reported at 85% for an intensive green roof; it was 33% for a conventional roof. A significant reduction in Pb, Zn, Cd, and Cu was also achieved.

The matrix in Table 6.1 shows the LCA components of the aforementioned references, i.e., system boundaries (modules covered) and environmental impacts considered. Observe that each study considers different life cycle stages. Some studies consider installation or maintenance; some do not.

Adding information on environmental impacts of the traditional and “green” systems, especially on installation (A5) and maintenance (B2) phases might change decisions. In terms of life cycle resource use, land use might be considered in decision making, as the pervious concrete system typically uses less land. Additional benefits of pervious concrete systems, such as ensuring improved water quality, helping to reduce flooding, and mitigating the heat island effect, may also be included in future research.

Table 6.1 Matrix on LCA components

System Boundaries	Module D Inclusion	Impact Categories and Resource Use	Reference
A1, A2, A3, A4, A5, B2, D	stormwater runoff storage and treatment	GWP, EP (freshwater and marine), EcoP (freshwater and marine), fossil fuel depletion	Wang et al. 2013
A1, A2, A3, D	runoff treatment	GWP, EP, Freshwater use, Solid waste	Sharma et al. 2009

System Boundaries	Module D Inclusion	Impact Categories and Resource Use	Reference
A1, A2, A3, A4, A5, B2, B3	-	Carbon footprint (kg CO_2-eq)	Vares and Pulakka 2015
A1, A2, A3, B2, D	runoff treatment	GWP	De Sousa et al. 2012
A1, A2, A3, A4, A5, C4, D	runoff treatment	ODP, AP, EP, GWP	Kosareo and Ries 2007
A1, A2, A3, A4, A5, B1, B2, B5, C1, C4, D	-	GWP, AP, HHCP, HHNCP, EP, ODP, EcoP, SCP	Flynn and Traver 2013
A1, A2, A3, D	runoff treatment	GWP	Spatari et al. 2011

GWP: Global Warming Potential; EP: Eutrophication Potential; EcoP: Ecotoxicity Potential; ODP: Ozone Depletion Potential; AP: Acidification Potential; HHCP: Human Health Cancer Potential; HHNCP: Human Health Non-cancer Potential; SCP: Smog Creation Potential

CHAPTER 7.0 EDUCATIONAL EFFICACY

The life cycle assessment (LCA) modules developed through these Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) grants are being widely used, as evidenced by continuing downloads from the CESTiCC website. The modules have been used in a second graduate-level course, and the use of narrated modules with discussion is seen as an effective method for teaching, while providing easy access to the material outside of class.

7.1 CESTiCC Analytics

Analytics were collected from the online website (CESTiCC) for accessing the modules and downloading them. These analytics may provide research data on the use of the modules for sustainability education. Note that in the LCA course described in Section 7.2, these modules were provided directly to the class and therefore are not included in the downloads. In addition, it is not known how often a download might be shared with others. Therefore, the data presented herein are conservative indicators of use.

Some of the LCA learning modules were uploaded to the CESTiCC website in 2015. However, collection of the analytics did not begin until October 2016. After this date, analytics were collected weekly for each module present on the website at that time. Several of the modules were uploaded in 2017 or 2018. In the tables in Appendix A, the title of each module and date of upload to the CESTiCC website are listed. Table 7.1 shows the total number of downloads of all modules from the CESTiCC website in the last quarter of 2016, 2017, and through March 2018. The number of downloads for each individual module is given in Appendix B in separate tables.

Table 7.1 Total number of downloads from the CESTiCC website

	2016 (4th quarter)	2017	2018 (1st quarter)
Total downloads	131	498	113

Figure 7.1 is a display of the number of downloads for the overview modules as captured in the fourth quarter of 2016 (starting the week of October 24), 2017, and the first quarter of 2018. Module A1 (Introduction to Life Cycle Assessment and ISO 14040) is downloaded more than other modules; it is the pivotal module introducing LCA as internationally standardized. It is interesting that Modules G2 and G3 (free tools and transportation tools) are downloaded more often than Module G1, which covers tools that cost money.

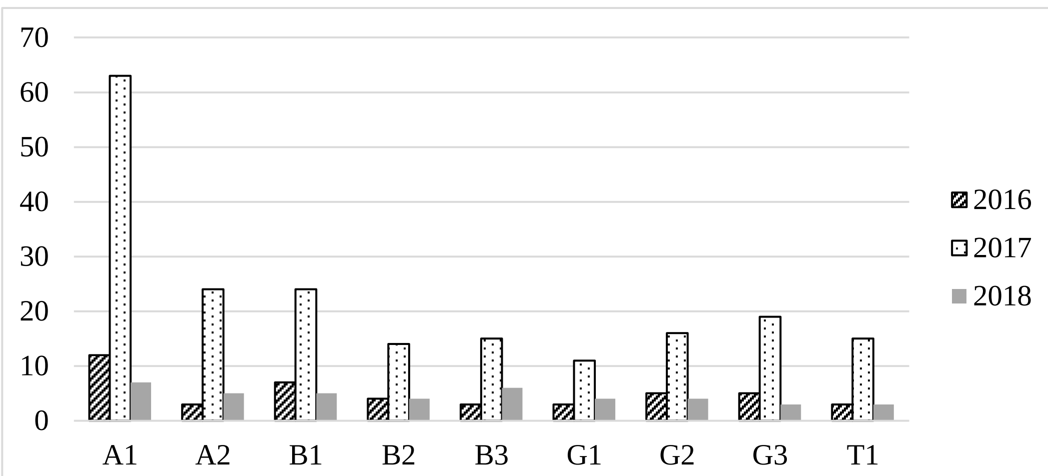


Figure 7.1 The number of downloads for the overview modules as captured in the 4th quarter of 2016 (starting October 24), 2017, and the 1st quarter of 2018 from the CESTiCC website

Figures 7.2 through 7.4 display the number of downloads for the detailed modules. Note the greater interest in the mandatory components of an ISO-compliant LCA as seen in α1, α2, and α3 than in the optional elements (α4). Note also the interest in EPDs (α6).

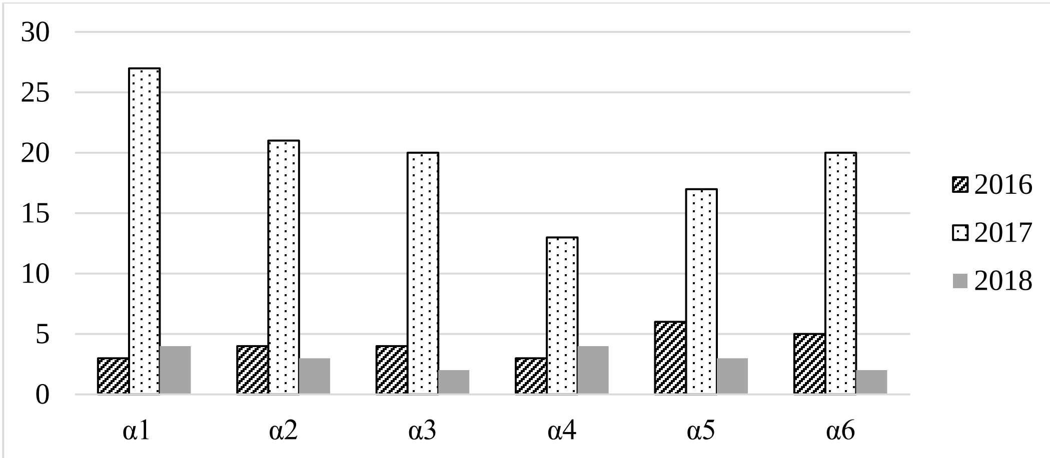


Figure 7.2 The number of downloads for the alpha (α) modules as captured in the 4th quarter of 2016 (starting October 24), 2017, and the 1st quarter of 2018 from the CESTiCC website

Figure 7.3 displays the beta (β) modules on environmental impact downloads. The most downloaded modules are Impact Assessment Methodologies (β9), Human Toxicity and Ecotoxicity Potential (β6), Human Health Particulate Matter (β7), and Global Warming Potential (β1).

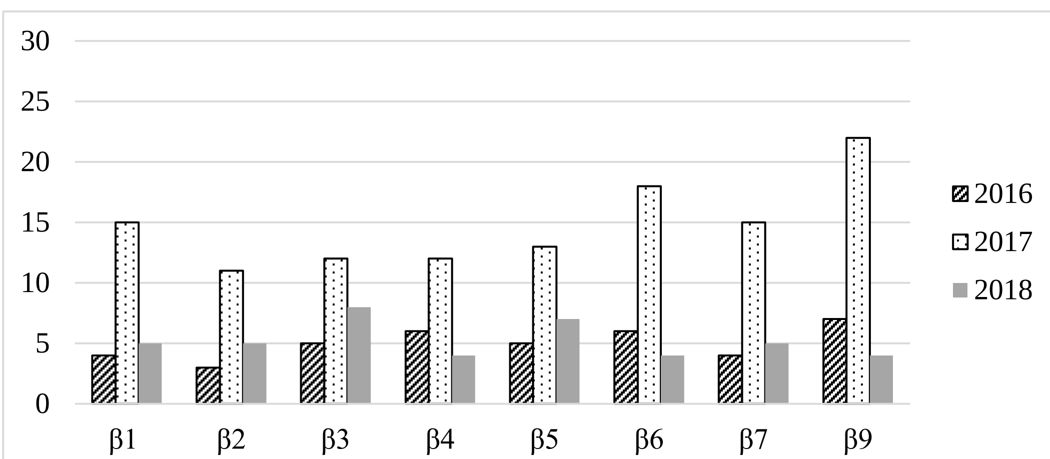


Figure 7.3 The number of downloads for the beta (β) modules as captured in the 4th quarter of 2016 (starting October 24), 2017, and the 1st quarter of 2018 from the CESTiCC website

Figure 7.4 displays the gamma (γ) modules on general LCA tools and selected tau (τ) modules, specifically those on transportation LCA tools. There appears to be a greater interest in the free transportation-related tools (τ3 and τ4).

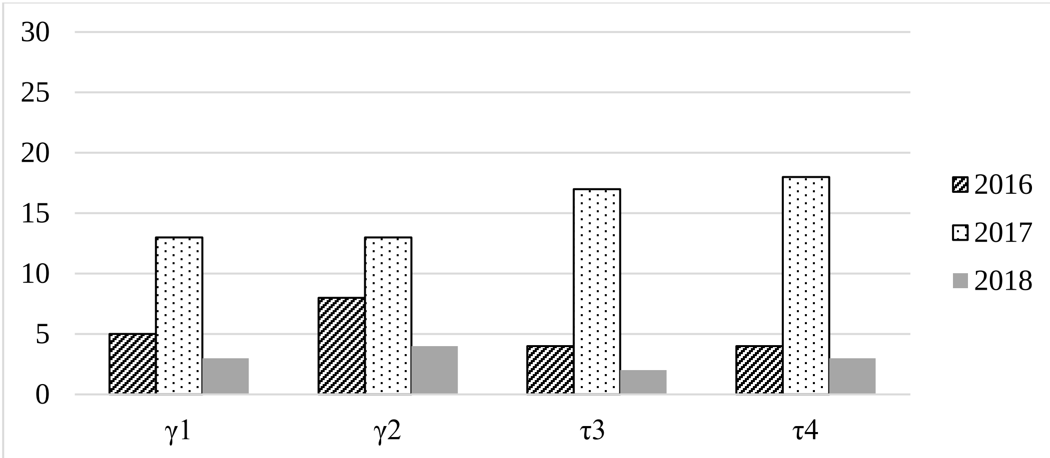


Figure 7.4 The number of downloads for the gamma (γ) and tau (τ) modules as captured in the 4th quarter of 2016 (starting October 24), 2017, and the 1st quarter of 2018 from the CESTiCC website

7.2 Lamar University Graduate Course: Life Cycle Assessment

During the spring 2017 semester, a graduate course, Life Cycle Assessment, was initiated in the Lamar University Civil and Environmental Engineering Department, using the modules for most of the lecture material. Sixteen students from different disciplines took this course. At the end of the semester, a survey on the Life Cycle Assessment modules was conducted. A sample questionnaire can be found in Appendix C. The following is a summary of the results of the survey.

In the first section of the questionnaire, students were asked to answer four questions and evaluate their overall satisfaction with the course. Students were asked to mark the given statements from 1 (least favored) to 5 (most favored). Table 7.1 shows the average results of the questions answered by sixteen graduate students.

Table 7.2 Overall results of LCA questionnaire (points out of five)

Question	Least 1 → Most 5
Question 1 (understanding content from modules only)	3.88
Question 2 (understanding content from modules plus discussion)	4.56
Question 3 (discussion stimulating further thought)	4.38
Question 4 (overall effectiveness of modules plus discussion)	4.63

There were positive and negative comments about the content of the modules and some suggestions for improvement. Questions 5 to 9 aimed to collect student comments on the course structure, especially regarding the pre-recorded modules. Positive comments included:

- Because of being pre-recorded, students can play, pause, and repeat the modules anytime
- Slides are available on web; if students lose the presentations, they can easily download
- Slides include visual materials, which helps students to remember things easily

Some students had negative comments:

- Slides are fast and the number of slides in each presentation is too large
- A preliminary discussion may help with understanding the modules

Several suggestions were made:

- Discussion time may be increased
- If the structure of the course is altered as 10 minutes pre-recorded modules with 20 minutes discussion section, this may help to better understand the concept
- Animations or videos may be added to modules.

CHAPTER 8.0 REFERENCES

Acero, A. P., Rodriguez, C., and Ciroth A. (2015). "LCIA methods: Impact assessment methods in Life Cycle Assessment and their impact categories," GreenDelta. <http://www.openlca.org/wp- content/uploads/2015/11/LCIA-METHODS-v.1.5.4.pdf> (accessed 23 February 2017).

ACI (American Concrete Institute). (2010). Report on Pervious Concrete. American Concrete Institute, Farmington Hills, MI.

AIST. (2012). *LIME 2 (Life-Cycle Impact Assessment Method Based on Endpoint Modelling)*. National Institute of Advanced Industrial Science and Technology (AIST), Japan.

Argonne National Laboratory (1993). GREET - Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation, The Energy Systems Division (ES) at Argonne National Laboratory, Argonne, IL.

Athena Institute (2014). User Manual and Transparency Document Impact Estimator for Buildings, v. 5, Athena Sustainable Materials Institute, Ontario, Canada.

Averyt, K., et al. (2011). Freshwater Use by U.S. Power Plants: Electricity's Thirst for a Precious Resource. A report of the Energy and Water in a Warming World Initiative, Cambridge, MA.

Bates, M. E., Fox-Lent, C., Seymour, L., Wender, B. A. and Linkov, I. (2015), "Life cycle assessment for dredged sediment placement strategies." *Science of the Total Environment*, 511 (Supplement C), 309–318.

BS EN. (2012) Sustainability of Construction Works. Environmental product declarations. Core rules for the product category of construction products. BS EN 15804:2012. British Standards, London, United Kingdom.

Butt, A. A., Mirzadeh, I., Toller, S., and Birgisson, B. (2014). "Life cycle assessment framework for asphalt pavements: methods to calculate and allocate energy of binder and additives." *Int. J. Pavement Eng.*, 15, 290–302.

Choudhary, S., Liang, S., Cai, H., Keoleian, G. A., Miller, S. A., Kelly, J., and Xu, M. (2014). "Reference and functional unit can change bioenergy pathway choices." *The International Journal of Life Cycle Assessment*, 19(4), 796–805.

CMU. (2015). Economic Input-Output Life Cycle Assessment (EIO-LCA). Carnegie Mellon University Green Design Institute, Pittsburgh, PA. <http://www.eiolca.net/> (accessed April 22, 2017).

CIRAIG, DTU, UM Ann Arbor, Quantis International, and EPFL. (2012). IMPACT World+. <http://www.impactworldplus.org/en/index.php>

De Sousa, M.R.C., Montalto, F. A., and Spatari, S. (2012). “Using Life Cycle Assessment to evaluate green and grey combined sewer overflow control strategies.” *Journal of Industrial Ecology*, 16(6), 901–913.

EC. (2010). ILCD Handbook (International Reference Life Cycle Data System): Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment, European Commission, Joint Research Centre, Institute for Environment and Sustainability, Luxembourg.

EI-99. (2000). Eco-indicator 99 Manual for Designers, A damage oriented method for Life Cycle Impact Assessment, Ministry of Housing, Spatial Planning and the Environment, Netherlands.

EPFL. (2003). *IMPACT (Impact Assessment of Chemical Toxins) 2002+ Methodology*. Swiss Federal Institute of Technology – Lausanne.

Fay, L., and Shi, X. (2012). “Environmental impacts of chemicals for snow and ice control: State of the knowledge.” *Water, Air and Soil Pollution*, 223, 2751–2770.

Fitch, G. M., Smith, J. A., and Clarens, A.F. (2013). “Environmental life-cycle assessment of winter maintenance treatments for roadways.” *Journal of Transportation Engineering*, 139(2), 138–146.

Flynn, K. M., and Traver, R. G. (2013). “Green infrastructure life cycle assessment: A bio-infiltration case study.” *Ecological Engineering*, 55, 9–22.

Georgia Tech. (2016). The Fuel and Emissions Calculator (FEC). Georgia Tech, School of Civil and Environmental Engineering, Atlanta, GA. <http://fec.ce.gatech.edu/> (accessed April 22, 2017).

Goedkoop, M. J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., and Van Zelm, R. (2009). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition Report I: Characterisation, 6 January 2009. <http://www.lcia-recipe.net>

GreenDelta (n.d.). Open LCA. <http://www.openlca.org/>

Grubb, D. G., et al. (2010). “Stabilized dredged material. I: Parametric study.” *Journal of Geotechnical and Geoenvironmental Engineering*, 136(8), 1011-1024.

Haselbach, L. (2017). Critical Review of LCA Treatment of Feedstock Energy. Final report to National Asphalt Pavement Association (NAPA).

Haselbach, L., and Langfitt, Q. (2015). Transportation Life Cycle Assessment Synthesis: Life Cycle Assessment Learning Module Series, Phase I. Report to Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) Project Number 101412, Pullman, WA.

Haselbach, L., and Temizel-Sekeryan, S. (2018). Inclusive reporting of feedstock energy and stored carbon: Asphalt case study.” *International Journal of Global Warming*, in press.

ifu. (2016). Umberto® NXT LCA User Manual, ifu Hamburg GmbH, Hamburg, Germany.

IPCC. (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 8.

ISO (International Organization for Standardization). (2006a). "Environmental management – Life cycle assessment – Principles and framework." *ISO 14040*, Geneva, Switzerland.

ISO (International Organization for Standardization). (2006b). "Environmental management – Life cycle assessment – Requirements and guidelines." *ISO 14044*, Geneva, Switzerland.

ISO (International Organization for Standardization). (2006c). "Environmental labels and declarations – Type III environmental declarations – Principles and procedures." *ISO 14025*, Geneva, Switzerland.

Kosareo, L., and Ries, R. (2007). "Comparative environmental life cycle assessment of green roofs." *Building and Environment*, 42, 2606–2613.

Langfitt, Q., and Haselbach, L. (2015). Life Cycle Assessment Synthesis for a Volume of Lubricating Oil in Marine Applications. ASCE Construction Institute: Environmental Sustainability in Transportation Infrastructure.

Langfitt, Q., and Haselbach, L. (2017). "Entity normalization in Life Cycle Assessment: Hybrid schemes applied to a transportation agency case study." *J. Industrial Ecology*, 21: 1090–1102.

Lippiatt, B. C. (2007). BEES 4.0 (Building for Environmental and Economic Sustainability) Technical Manual and User Guide. National Institute of Standards and Technology (NIST), Gaithersburg, MD.

Mohareb, E., and Kennedy, C. (2012). "Gross direct and embodied carbon sinks for urban inventories." *Journal of Industrial Ecology*, 16(3), 302–316.

NAPA. (2014). Fast Facts. National Asphalt Pavement Association. Lanham, MD. <https://www.asphaltpavement.org/PDFs/GovAffairs/NAPA%20Fast%20Facts%2011-02-14%20Final.pdf> (accessed September 19, 2017).

PE International. (2012). GaBi Manual, PE International Ag., Stuttgart, Germany.

Peng, B., Cai, C., Yin, G., Li, W., and Zhan, Y. (2015). "Evaluation system for CO2 emission of hot asphalt mixture." *Journal of Traffic and Transportation Engineering* (English edition), 2(2), 116–124.

Potting, J., and Hauschild, M. (2004). Background for Spatial Differentiation in Life Cycle Impact Assessment – The EDIP2003 Methodology. Danish Environmental Protection Agency, Copenhagen.

PRé (2016). SimaPro Database Manual Methods Library 2.9, San Francisco, CA.

Quantis. (2013). “QS Product Free 1 intro tour.” YouTube, <https://www.youtube.com/watch?v=QRHaD91rxwA>

RMRC-3G. (2003). “PaLATE 2.0.” Recycled Materials Resource Center, University of Wisconsin-Madison, Madison, WI. <http://rmrc.wisc.edu/palate/> (accessed March 31, 2017).

Schepper, M., Heede, P., Driessche, I., and Belie, N. (2014). “Life Cycle Assessment of completely recyclable concrete.” *Materials*, 7, 6010–6027.

Sharma, A. K., Grant, A. L., Grant, T., Pamminger, F., and Opray, L. (2009). “Environmental and economic assessment of urban water services for a Greenfield development.” *Environmental Engineering Science*, 26(5), 921–934.

Simonen, K., and Haselbach, L. (2012). “Environmental Product Declarations: U.S. Policy and Market Drivers and Implications for the Concrete Industry.” Presentation at the *NRMCA Sustainability Conference*, Seattle, WA, May.

Spatari, S., Yu, Z., and Montalto, F. A. (2011). “Life cycle implications of urban green infrastructure.” *Environmental Pollution*, 159(8–9), 2174–2179.

Surya, M., Kanta Rao, V.V.L., and Lakshmy, P. (2013). “Recycled aggregate concrete for transportation infrastructure.” *2nd Conference of Transportation Research Group of India* (2nd CTRG), Procedia – Social and Behavioral Sciences 104, 1158–1167.

Toffoletto et al. (2007). “LUCAS – A new LCIA method used for a Canadian-specific context.” *Int. J. of LCA*, 12(2), 93–102.

U.S. EPA. (n.d.) “Pervious Pavement Alternatives.” PCA Northeast Cement Shippers Association. <https://archive.epa.gov/region02/njgiforum/web/pdf/08justice.pdf> (accessed February 24, 2018).

U.S. EPA. (2007). “Identifying, Planning, and Financing Beneficial Use Projects Using Dredged Material, Beneficial Use Planning Manual.” <https://www.epa.gov/sites/production/files/2015-08/documents/identifying_planning_and_financing_beneficial_use_projects.pdf> (accessed July 30, 2017).

U.S. EPA. (2012a). “Report to congress on Black Carbon – EPA-450/R-12-001.” <http://www3.epa.gov/blackcarbon/2012report/fullreport.pdf>

U.S. EPA. (2012b). Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) TRACI, version 2.1, Users Guide, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

U.S. EPA. (2015). “Asphalt concrete.” <https://www3.epa.gov/warm/pdfs/Asphalt_Concrete.pdf> (accessed July 8, 2017).

U.S. FHWA. (2004). *Transportation Applications of Recycled Concrete Aggregate, FHWA State of the Practice National Review*. U.S. Department of Transportation, Federal Highway Administration.

Vares, S., and Pulakka, S. (2015). Life Cycle assessment (LCA) and Costing Analysis (LCCA) for Conventional and Permeable Pavement Walkways. Research Report to VTT Technical Research Centre of Finland, VTT-R-00068-15.

Ventura, A., and Santero, N. (2012). "Organic materials for construction: Questioning the concept of feedstock energy." *International Symposium on Life Cycle Assessment and Construction*, Nantes, France

Walker, T., Cardellichio, P., Gunn, J. S., Saah, D. S., and Hagan, J. M. (2013). "Carbon accounting for woody biomass from Massachusetts (USA) managed forests: A framework for determining the temporal impacts of wood biomass energy on atmospheric greenhouse gas levels." *Journal of Sustainable Forestry*, 32:1–2, 130–158.

Wang, R., Eckelman, M. J., and Zimmerman, J. B. (2013). "Consequential environmental and economic life cycle assessment of green and gray stormwater infrastructures for combined sewer systems." *Environmental Science and Technology*, 47, 11189–11198.

Ye, Z., Xu, Y., Veneziano, D., and Shi, X. (2014). "Evaluation of winter maintenance chemicals and crashes with an artificial neural network." *Transportation Research Record: Journal of the Transportation Research Board*, 2440, 43–50.

APPENDIX A

Table A.1 Modules in Group A and α: ISO Compliant LCA

Group A and α – ISO Compliant LCA	**Date Uploaded to CESTiCC Website**	**Date Uploaded to Lamar Website**
Module A1 - Introduction to Life Cycle Assessment and ISO 14040	February 2015	January 2018
Module A2 - LCA Requirements and Guidelines: ISO 14044	February 2015	January 2018
Module α1 - Goal, Function, and Functional Unit	February 2015	January 2018
Module α2 - System, System Boundary, and Allocation	February 2015	January 2018
Module α3 - Life Cycle Stages	April 2015	January 2018
Module α4 - LCIA Optional Elements: Grouping, Weighing, and Normalization	November 2015	January 2018
Module α5 - Data Types and Sources	December 2015	January 2018
Module α6 - Environmental Product Declarations (EPDs)	December 2015	January 2018
Module α7 - Feedstock energy and carbon accounting for asphalt and other materials	December 2017	January 2018

Table A.2 Modules in Group B and β: Environmental Impact Categories

Group B and β – Environmental Impact Categories	**Date Uploaded to CESTiCC Website**	**Date Uploaded to Lamar Website**
Module B1 - Introduction to Impact Categories	April 2015	January 2018
Module B2 - Common Air Emissions Impact Categories	March 2015	January 2018
Module B3 - Other Common Emissions Impact Categories	March 2015	January 2018
Module β1 - Global Warming Potential	December 2015	January 2018
Module β2 - Acidification Potential	September 2015	January 2018
Module β3 - Ozone Depletion Potential	September 2015	January 2018
Module β4 - Smog Creation Potential	September 2015	January 2018
Module β5 - Eutrophication Potential	September 2015	January 2018
Module β6 - Human Toxicity and Ecotoxicity Potential	October 2015	January 2018
Module β7 - Human Health Particulate Matter	September 2015	January 2018
Module β8 - Resource-based and other impacts	April 2018	April 2018
Module β9 - Impact Assessment Methodologies	October 2015	January 2018
Module β10 - Particulate Matter and Effects on GWP	December 2017	January 2018

Table A.3 Modules **in** Group G and γ: General LCA Tools

Group G and γ – General LCA Tools	**Date Uploaded to CESTiCC Website**	**Date Uploaded to Lamar Website**
Module G1 - General Paid LCA Software Tools	February 2015	January 2018
Module G2 - General Free LCA Software Tools	March 2015	January 2018
Module G3 - Transportation LCA Software Tools	October 2015	January 2018
Module γ1 - EIO-LCA Tutorial and Links to GaBi Tutorials	October 2015	January 2018
Module γ2 - Building LCA Software Tutorial	October 2015	January 2018

Table A.4 Modules in Groups T and τ: Transportation LCA

Groups T and τ – Transportation LCA	**Date Uploaded to CESTiCC Website**	**Date Uploaded to Lamar Website**
Module T1 - Introduction to Transportation LCA and Literature Review	September 2015	January 2018
Module τ1 - Functional Units in Transportation	April 2018	April 2018
Module τ2 - Agency and Hybrid Normalization	December 2017	January 2018
Module τ3 - GREET Tutorial	November 2015	January 2018
Module τ4 - Athena Impact Estimator for Highways	October 2015	January 2018
Module τ5 - Case Study - Washington State Ferries Oil Filtration	December 2017	January 2018

Module τ6 - Asphalt Recycling	December 2017	January 2018
Module τ7 - Concrete Recycling	April 2018	April 2018
Module τ8 - Stabilization of Dredged Material for Beneficial Uses: A Transportation Challenge	December 2017	January 2018
Module τ9 - Impact of Deicers on Transportation Systems	April 2018	April 2018

APPENDIX B

Table B.1 Analytics for Modules in Group A and α: ISO Compliant LCA (time frame is the 4th quarter of 2016, 2017, and the 1st quarter of 2018)

Group A and α – ISO Compliant LCA	**Number of Downloads**			
	CESTiCC Website			**LU Website**
	2016	**2017**	**2018**	**2018**
Module A1 - Introduction to Life Cycle Assessment and ISO 14040	12	63	7	4
Module A2 - LCA Requirements and Guidelines: ISO 14044	3	24	5	8
Module α1 - Goal, Function, and Functional Unit	3	27	4	4
Module α2 - System, System Boundary, and Allocation	4	21	3	4
Module α3 - Life Cycle Stages	4	20	2	8
Module α4 - LCIA Optional Elements: Grouping, Weighing, and Normalization	3	13	4	4
Module α5 - Data Types and Sources	6	17	3	4
Module α6 - Environmental Product Declarations (EPDs)	5	20	2	4
Module α7 - Feedstock energy and carbon accounting for asphalt and other materials	N/A	0	0	8

Table B.2 Analytics for Modules in Group B and β: Environmental Impact Categories (time frame is the 4th quarter of 2016, 2017, and the 1st quarter of 2018)

Group B and β – Environmental Impact Categories	**Number of Downloads**			
	CESTiCC Website			**LU Website**
	2016	**2017**	**2018**	**2018**
Module B1 - Introduction to Impact Categories	7	24	5	43
Module B2 - Common Air Emissions Impact Categories	4	14	4	12
Module B3 - Other Common Emissions Impact Categories	3	15	6	8
Module β1 - Global Warming Potential	4	15	5	12
Module β2 - Acidification Potential	3	11	5	8
Module β3 - Ozone Depletion Potential	5	12	8	4
Module β4 - Smog Creation Potential	6	12	4	4
Module β5 - Eutrophication Potential	5	13	7	4
Module β6 - Human Toxicity and Ecotoxicity Potential	6	18	4	4
Module β7 - Human Health Particulate Matter	4	15	5	8
Module β8 - Resource-based and other impacts	N/A	N/A	N/A	N/A
Module β9 - Impact Assessment Methodologies	7	22	4	4
Module β10 - Particulate Matter and Effects on GWP	N/A	0	0	8

Table B.3 Analytics for Modules in Group G and γ: General LCA Tools (time frame is the 4th quarter of 2016, 2017, and the 1st quarter of 2018)

Group G and γ – General LCA Tools	**Number of Downloads**			
	CESTiCC Website			**LU Website**
	2016	**2017**	**2018**	**2018**
Module G1 - General Paid LCA Software Tools	3	11	4	4
Module G2 - General Free LCA Software Tools	5	16	4	4
Module G3 - Transportation LCA Software Tools	5	19	3	4
Module γ1 - EIO-LCA Tutorial and Links to GaBi Tutorials	5	13	3	4
Module γ2 - Building LCA Software Tutorial	8	13	4	4

Table B.4 Analytics for Modules in Groups T and τ: Transportation LCA (time frame is the 4th quarter of 2016, 2017, and the 1st quarter of 2018)

Groups T and τ – Transportation LCA	**Number of Downloads**			
	CESTiCC Website			**LU Website**
	2016	**2017**	**2018**	**2018**
Module T1 - Introduction to Transportation LCA and Literature Review	3	15	3	4
Module τ1 - Functional Units in Transportation	N/A	N/A	N/A	N/A
Module τ2 - Agency and Hybrid Normalization	N/A	0	0	4
Module τ3 - GREET Tutorial	4	17	2	4
Module τ4 - Athena Impact Estimator for Highways	4	18	3	4
Module τ5 - Case Study - Washington State Ferries Oil Filtration	N/A	0	0	8
Module τ6 - Asphalt Recycling	N/A	0	0	16
Module τ7 - Concrete Recycling	N/A	N/A	N/A	N/A
Module τ8 - Stabilization of Dredged Material for Beneficial Uses: A Transportation Challenge	N/A	0	0	4
Module τ9 - Impact of Deicers on Transportation Systems	N/A	N/A	N/A	N/A

APPENDIX C

Life Cycle Assessment Module Questionnaire

This survey is examining the appropriateness of using pre-recorded audio/visual education modules in courses and workshops. The goal is to determine various advantages and disadvantages of the approach to aid in determining its applicability as a sustainability educational tool. Please provide answers to the following 5-point scale and short answer questions. Thank you for your feedback!

Please circle one number for each question — Least → Most

1)	How well did you understand the content as it was presented in the modules (prior to discussion)?	1	2	3	4	5
2)	How much did the discussion help you understand the content in the modules?	1	2	3	4	5
3)	How much did the discussion stimulate further thought beyond what was presented in the modules?	1	2	3	4	5
4)	Overall, how effective were the modules and discussion in furthering your knowledge on the topics presented?	1	2	3	4	5

5) What do you think are the benefits of using pre-recorded modules followed by discussion as an educational tool?

6) What do you think are the negative aspects of using pre-recorded modules followed by discussion as an educational tool?

7) In which settings do you think the use of pre-recorded modules is appropriate?

a) Without discussion component:____________________

b) With discussion component:____________________

8) Please comment on the length of the:

a) Pre-recorded modules: ____________________

b) Discussion time: ____________________

9) Do you have any other suggestions? (continue on back if more space needed)

DO NOT ANSWER - FOR OFFICIAL USE ONLY

Setting: Workshop WSU Course Brazil Course Lamar Course

Modules used: ____ ____ ____ ____ ____ ____ ____ ____

Discussion length: ____ ____ ____ ____ ____ ____ ____ ____

Figure C.1 Sample LCA module questionnaire form